Perturbative QCD
and
Hard Probes

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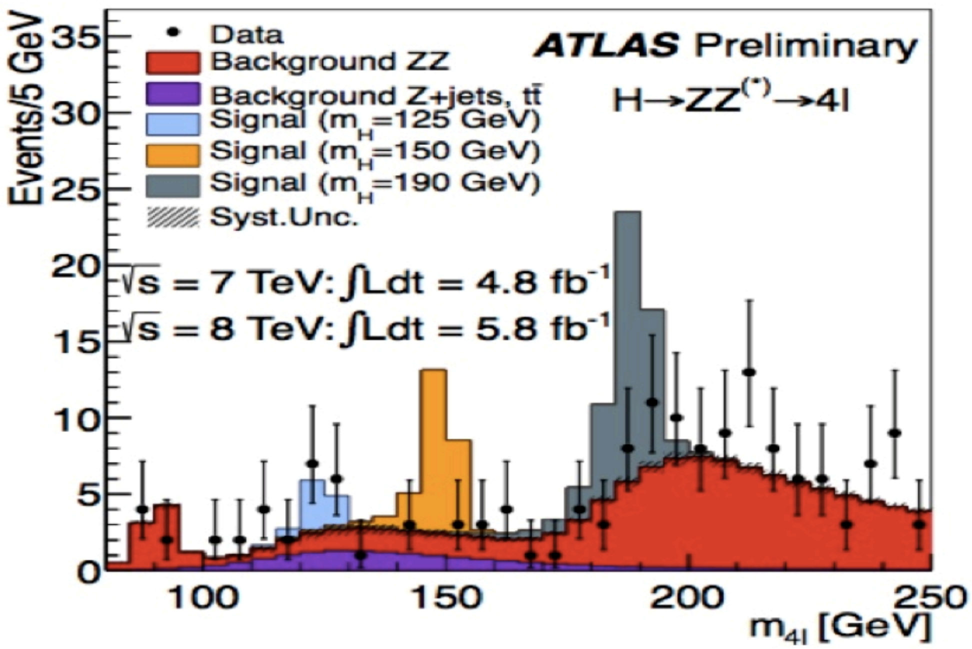
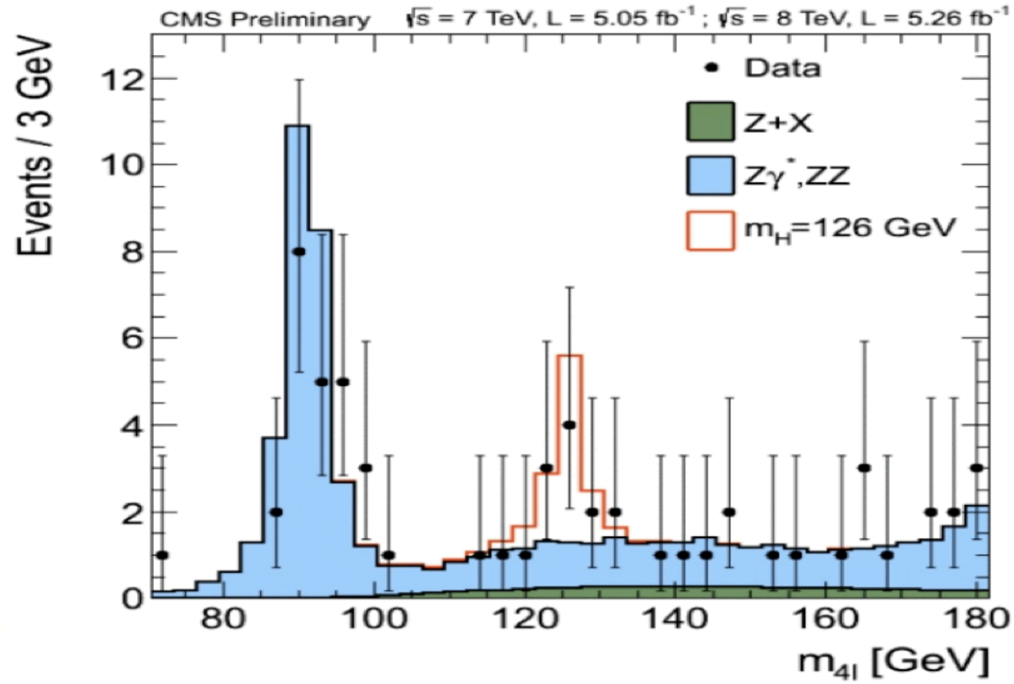
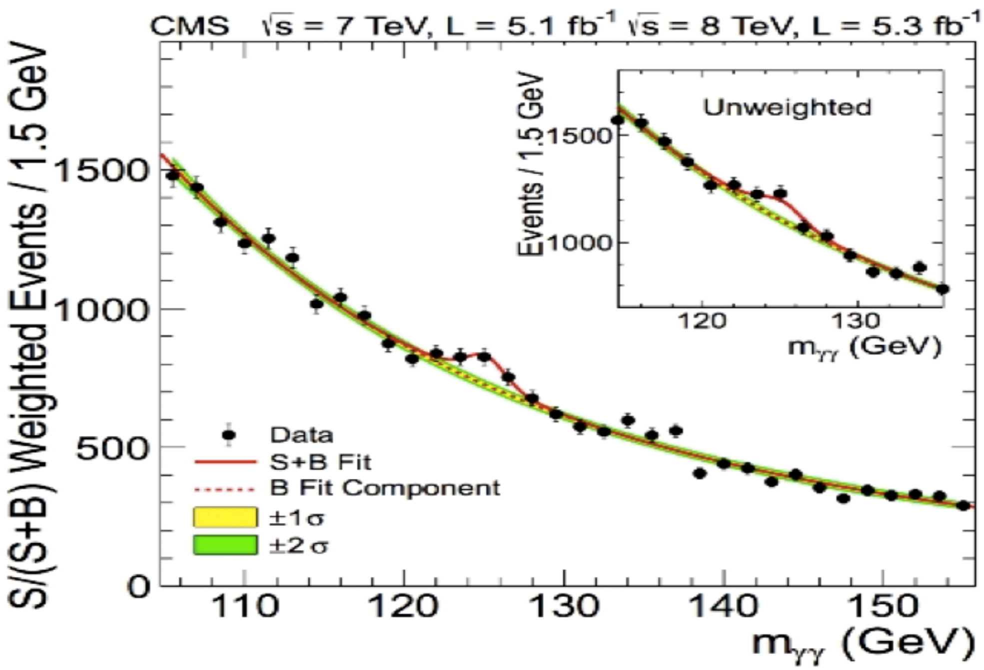
The big story - discovery of Higgs boson







Physicists Find Elusive Particle Seen as Key to Universe

Pool photo by Denis Balibouse

Mass without mass?

- **Higgs mechanism – often credited with mass generation:**

  But, generates too little to be relevant to the mass of our visible world!

- **QCD and Mass of hadrons:**
  - ✧ Hadron mass:

    Lattice QCD calculation

  - ✧ Mystery – mass scale?

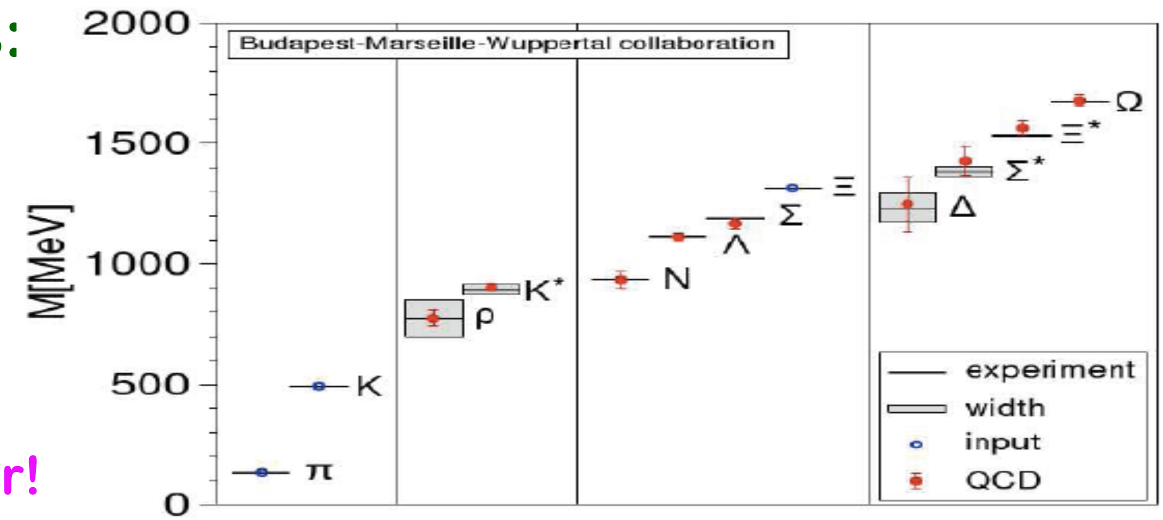
    Other than quark mass,
    QCD has no mass parameter!

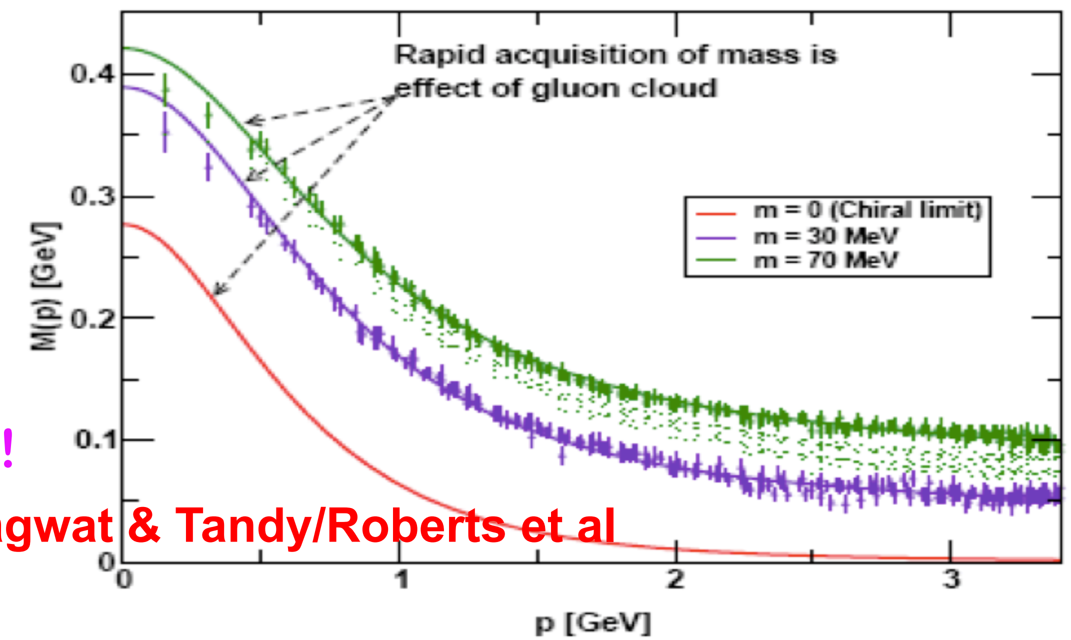
    How QCD generates
    hadron mass?

  - ✧ "Quark" Mass function:

$$S_F(p) = \frac{\mathcal{F}(p)}{\not{p} - \mathcal{M}(p)}$$

No-linear gluon-self interaction!





Bhagwat & Tandy/Roberts et al

Mass without mass?

Challenges to QCD and hadron physics

❑ **Emergence of hadrons from quarks and gluons:**

Hadron properties		QCD		
Charge, Mass, Spin, Magnetic moment, …	⟷	Quarks Color, Flavor, Charge, Mass, Spin, …	+	Gluons Color, Spin, …

❑ **Questions:**

✧ Hadron's partonic structure – parton space-time distributions?

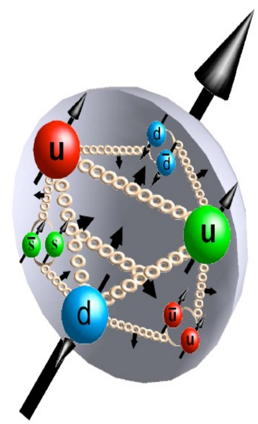
✧ Parton's confined motion inside a hadron?

✧ Hadron property in terms of dynamics of quarks and gluons?

✧ Formation of hadrons out of produced partons?

✧ Nuclear properties if we only see quarks and gluons?

✧ …



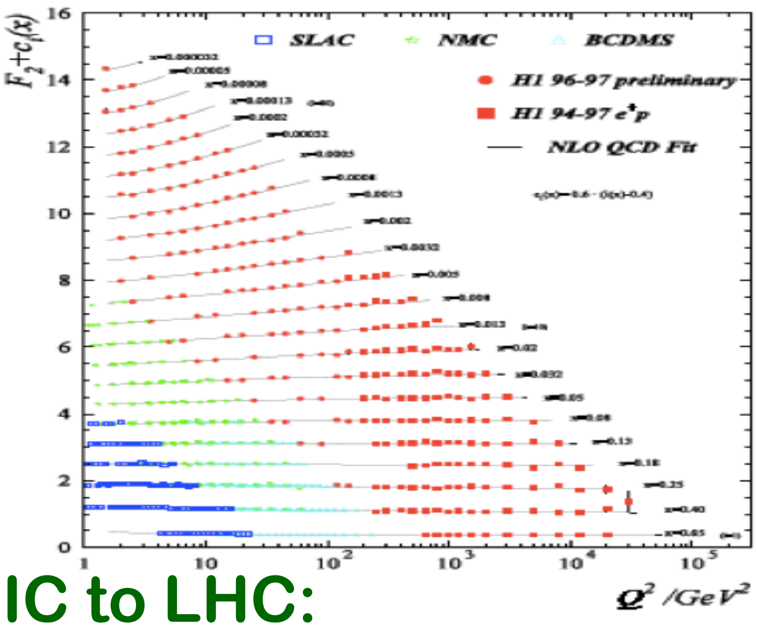
We need sharp probes to "see" quarks and gluons!

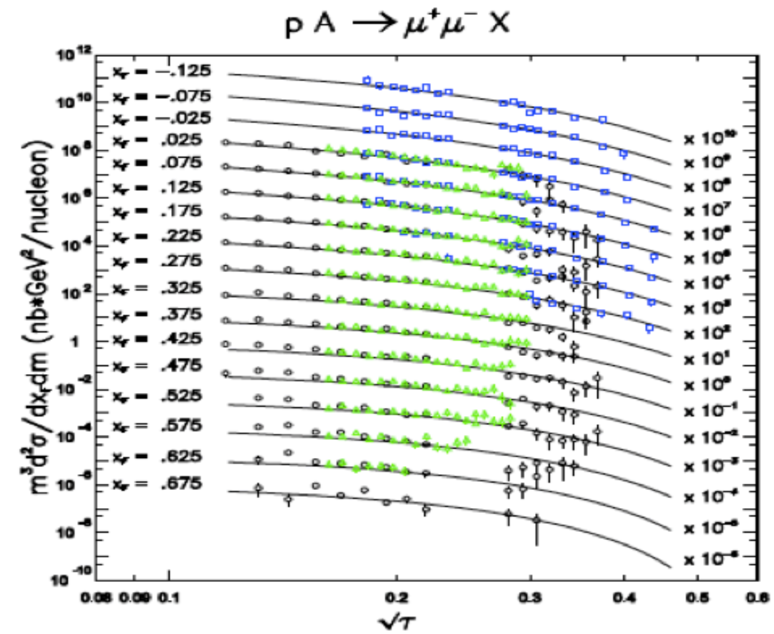
We believe QCD – experimental tests

- ❑ **From DIS to Drell-Yan:**

The probe:

< 0.1 fm

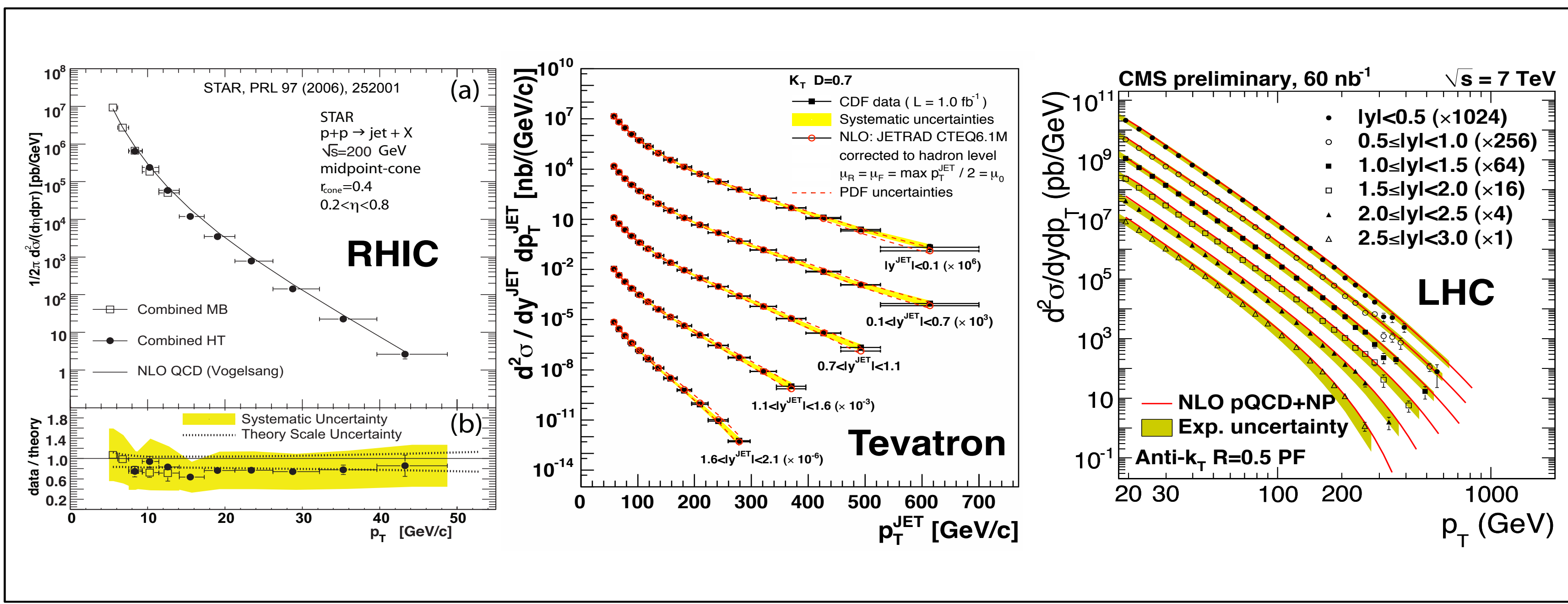




- ❑ **From RHIC to LHC:**

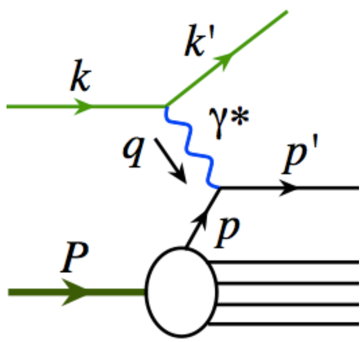
The probe:

<< 0.1 fm



The clean colorless probes

❑ DIS:

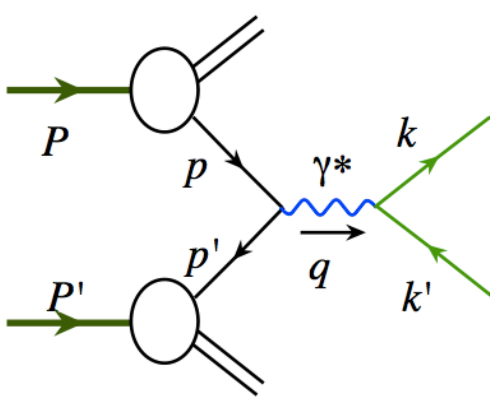


$$\left.\begin{array}{l} q^2 < 0 \\ \\ P^2 \approx 0 \end{array}\right\} \xrightarrow{\text{Lorenz transformation}} \left\{\begin{array}{l} q^\mu = (0, \vec{0}_\perp, -Q) \\ q^2 = -Q^2 \\ p^\mu = (\frac{Q}{2}, \vec{0}_\perp, \frac{Q}{2}) \\ p'^\mu = (\frac{Q}{2}, \vec{0}_\perp, -\frac{Q}{2}) \end{array}\right.$$

Natural event structure:

- ✧ Scattered quark moving backwards – 1D!
- ✧ Preserve parton's transverse momentum! $\vec{0}_\perp \to \vec{k}_\perp$

❑ Drell-Yan:



$$\left.\begin{array}{l} q^2 > 0 \\ P^2 \approx 0 \\ P'^2 \approx 0 \end{array}\right\} \xrightarrow{\text{Lorenz transformation}} \left\{\begin{array}{l} q^\mu = (Q, \vec{0}_\perp, 0) \\ q^2 = Q^2 > 0 \\ p^\mu = (\frac{Q}{2}, \vec{0}_\perp, \frac{Q}{2}) \\ p'^\mu = (\frac{Q}{2}, \vec{0}_\perp, -\frac{Q}{2}) \end{array}\right.$$

Natural event structure:

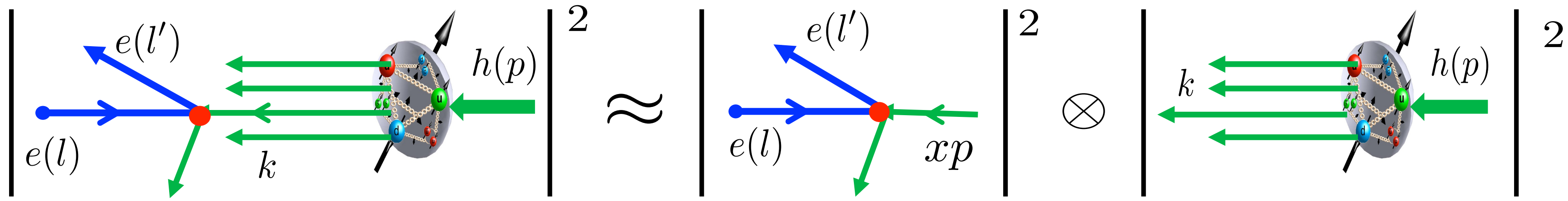
- ✧ 1D – annihilation!
- ✧ Vector sum of partons' transverse momenta!

QCD at a sub-femtometer scale

❑ QCD factorization:

- ✧ PQCD cannot calculate any cross sections with identified hadron(s)!
- ✧ Hard scattering is localized in space-time to 1/Q

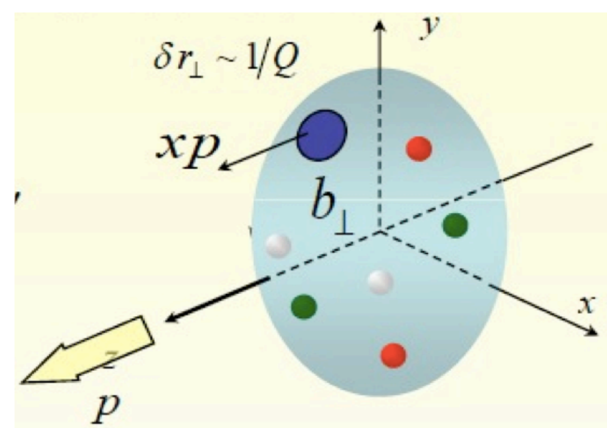
  Dynamics at hadronic scale is effectively frozen
- ✧ Quantum interference between two scales is suppressed by $\left(\frac{1/\mathrm{fm}}{Q}\right)^n$



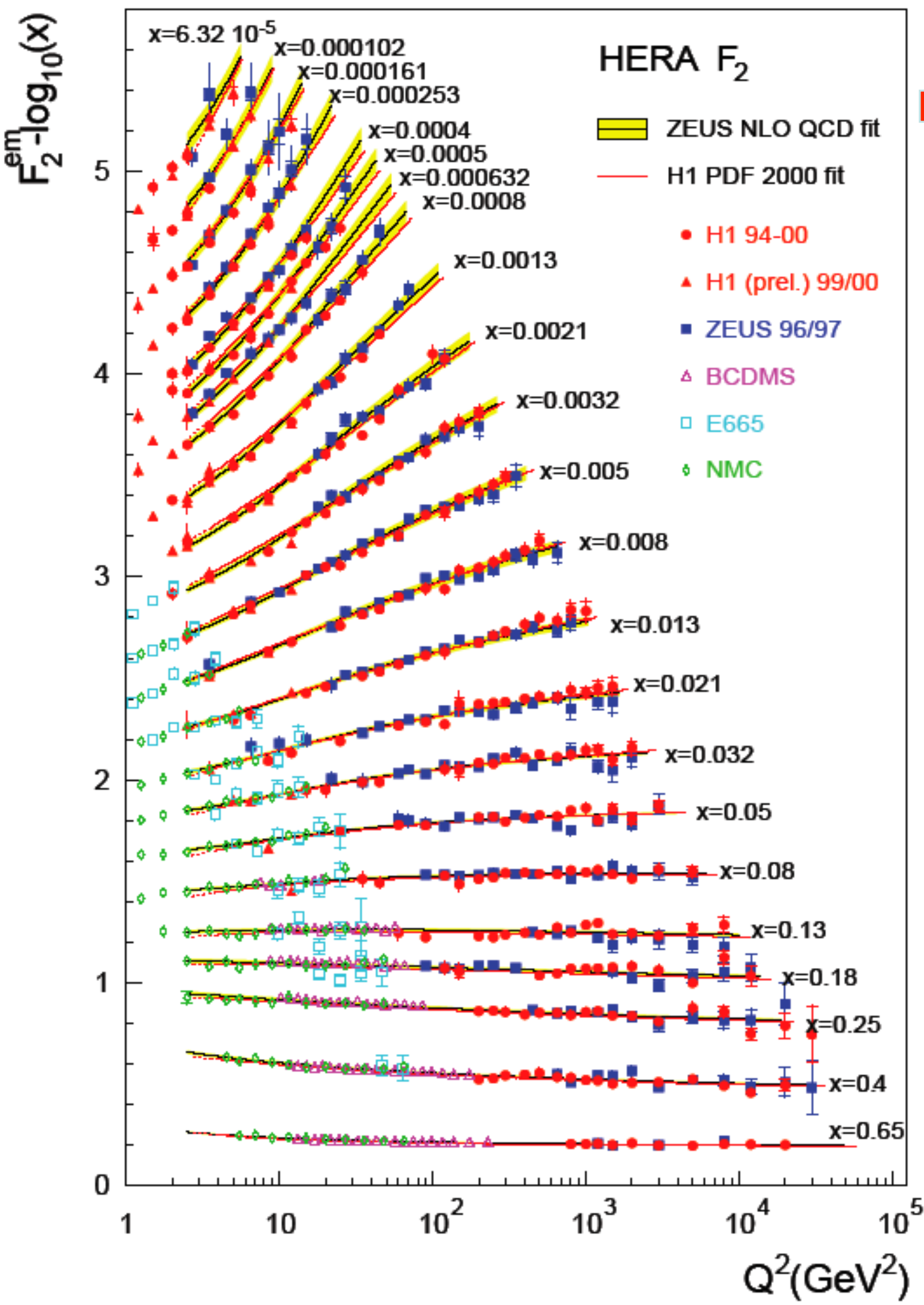
Cross section femtometer probe Parton in a hadron

❑ Parton distribution: $\phi_{f/h}(x,\mu^2)$

- ✧ Not unique, Not physical, …
- ✧ =\= hadron wave function squared!
- ✧ "measurable" – dilute approximation
- ✧ Integrate over all parton's k_T (avg. over b_T)
- ✧ Process independent – predictive power!



1D - Parton distribution functions from HERA

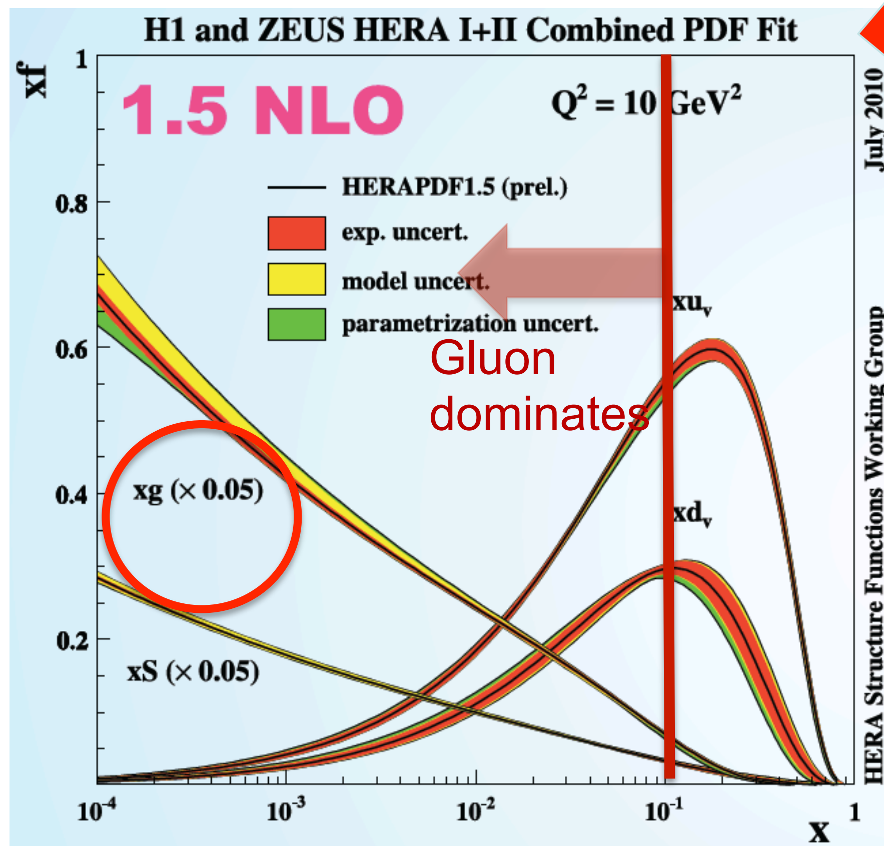


✧ Scaling violation of F2(x,Q2)

$$\frac{\partial F_2(x,Q^2)}{\partial \ln Q^2} \propto G(x,Q^2)$$

✧ NLO QCD global analyses:

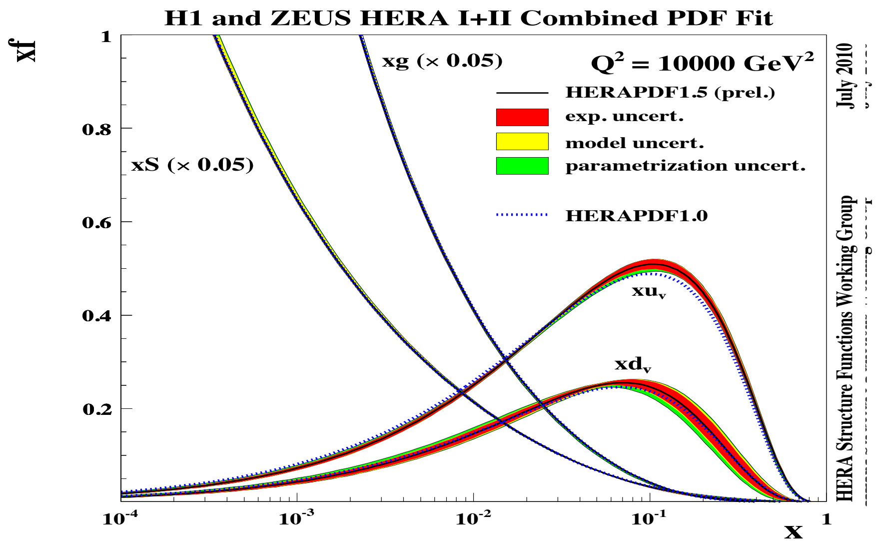
Fit data with linear DGLAP equation



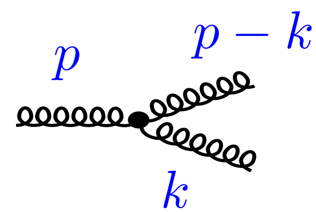
Fit almost all data with Q > 2 GeV

New regime of QCD matter

❑ Proliferation of soft gluons:



✧ **Radiation:**



$$d\mathcal{P} \sim \alpha_s \frac{dk_T^2}{k_T^2}\,\frac{dx}{x}$$

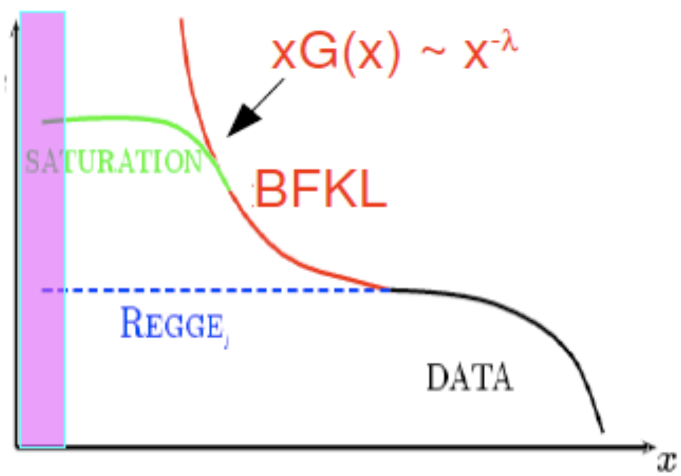
✧ **Evolution:**

DGLAP $\qquad \dfrac{dk_T^2}{k_T^2} \to d\log(Q^2)$

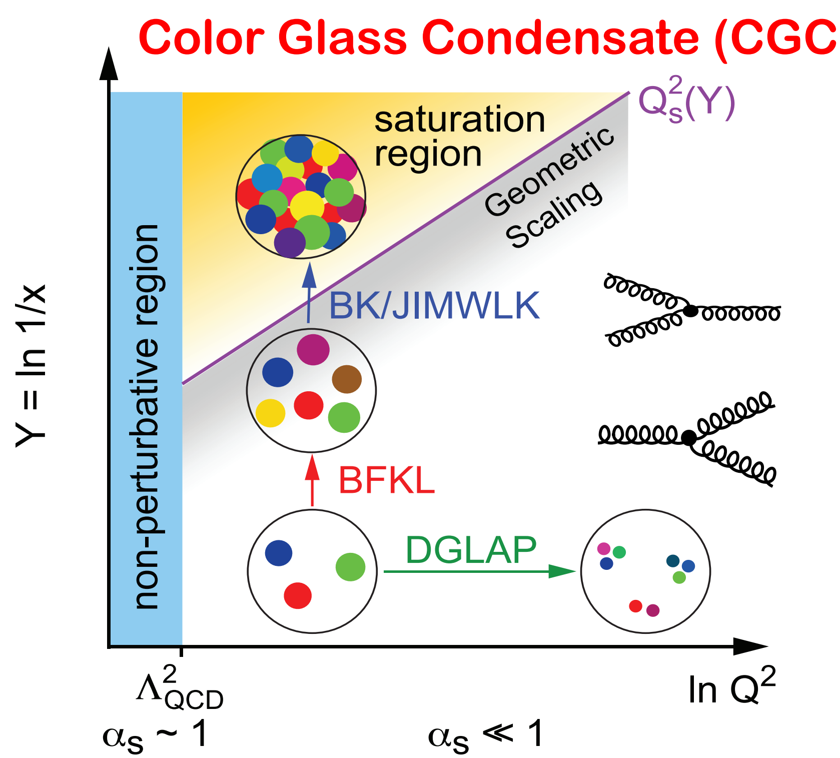
BFKL $\qquad \dfrac{dx}{x} \to d\log(1/x)$

❑ Indefinite rise at low x?

$xG(x) = dN_g/dy$



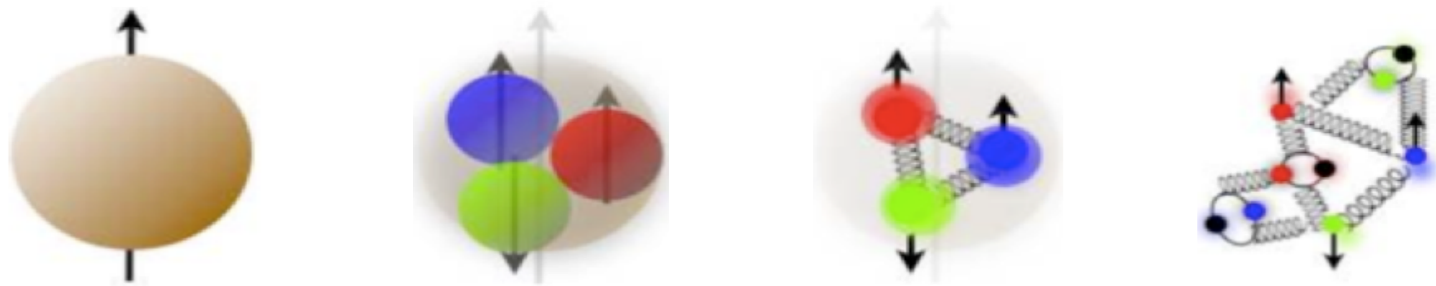
Can we find it for sure?



Proton spin and proton structure?

❑ Complexity of a proton state in QCD:

$$S(\mu) = \sum_f \langle P, S | \hat{J}_f^z(\mu) | P, S \rangle = \frac{1}{2} \equiv J_q(\mu) + J_g(\mu) = \frac{1}{2}\Sigma(\mu) + L_q(\mu) + J_g(\mu)$$

$S(\mu) = \frac{1}{2}$  $\mu \Rightarrow \infty$

❑ Over 20 years effort:

✧ Quark (valence + sea) helicity: $\sim 30\%$ of proton spin

✧ Gluon helicity (RHIC data): Not zero, but, small

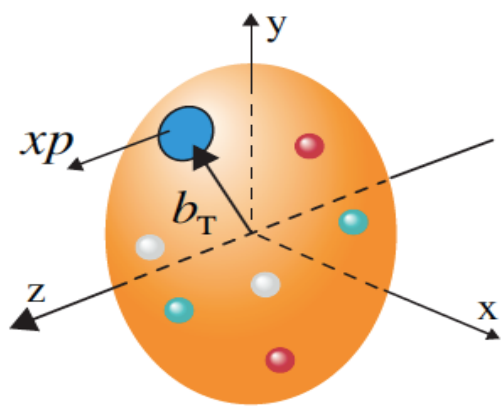
➡ How to explore the gluon and sea quark contribution?

❑ Tomographic images:

✧ Spatial images?

GPDs

Confined distribution?



✧ Momentum images?

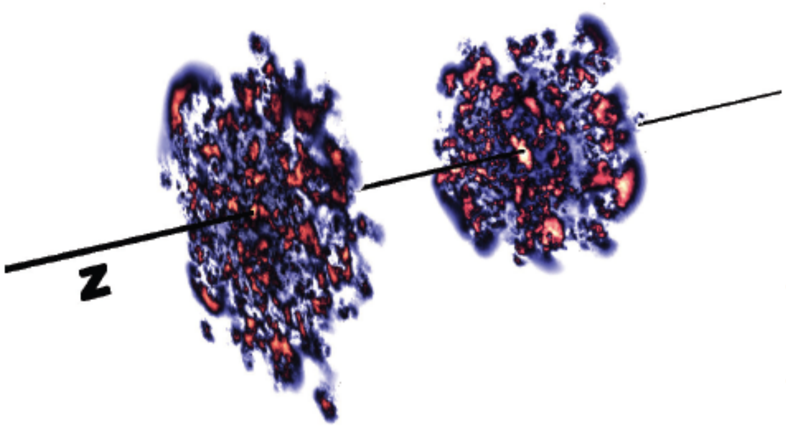
TMDs

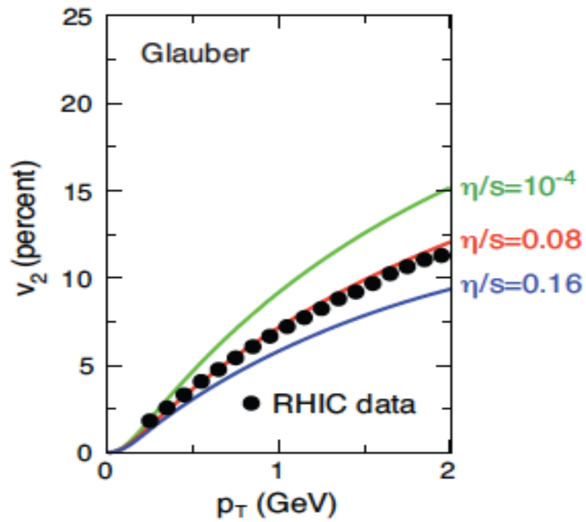
Confined motion?

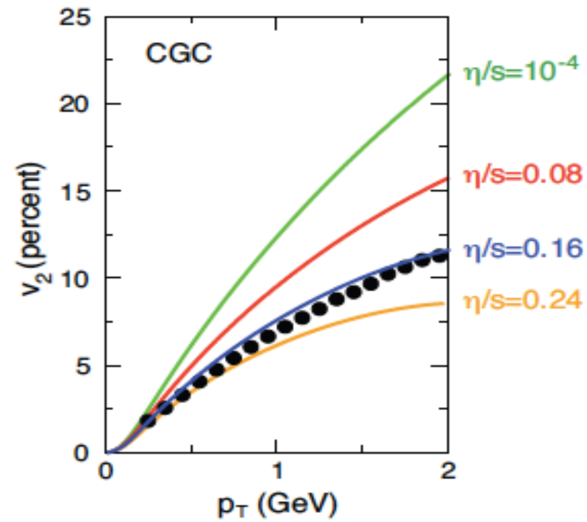
Initial condition of heavy ion collisions?

❑ Gluon density fluctuation:

$$\frac{dN}{d\phi} = \frac{N}{2\pi}\left(1 + \sum_n 2\, v_n \cos(n\tilde{\phi})\right)$$

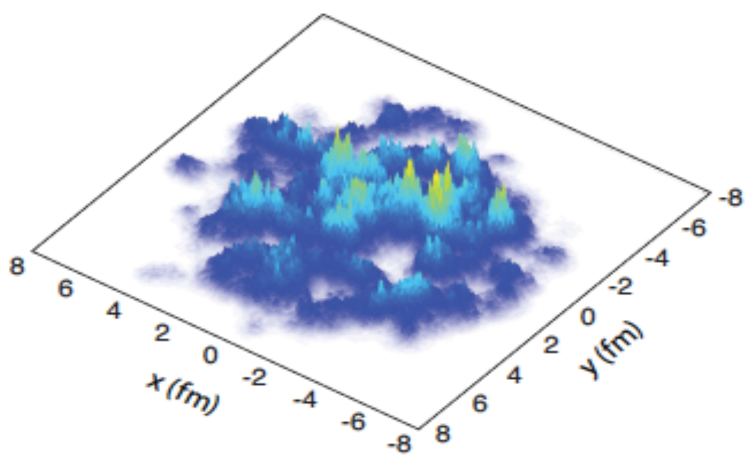


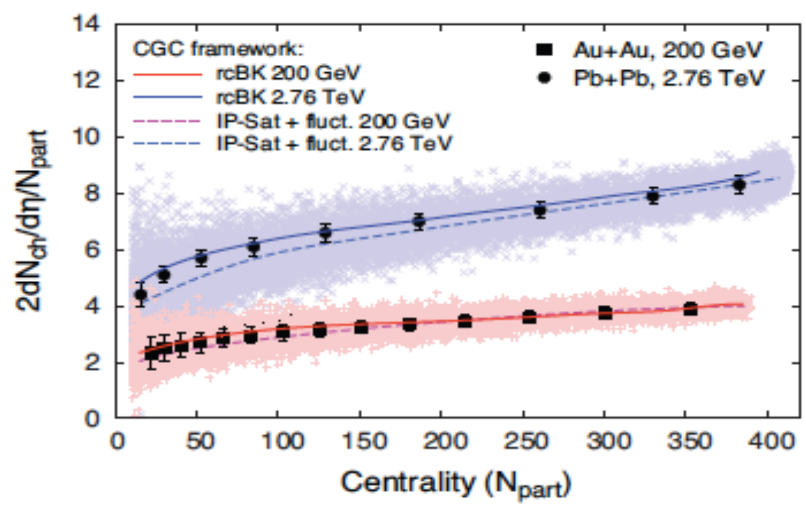




+ Viscous relativistic hydrodynamics

❑ Multiplicity – CGC model:





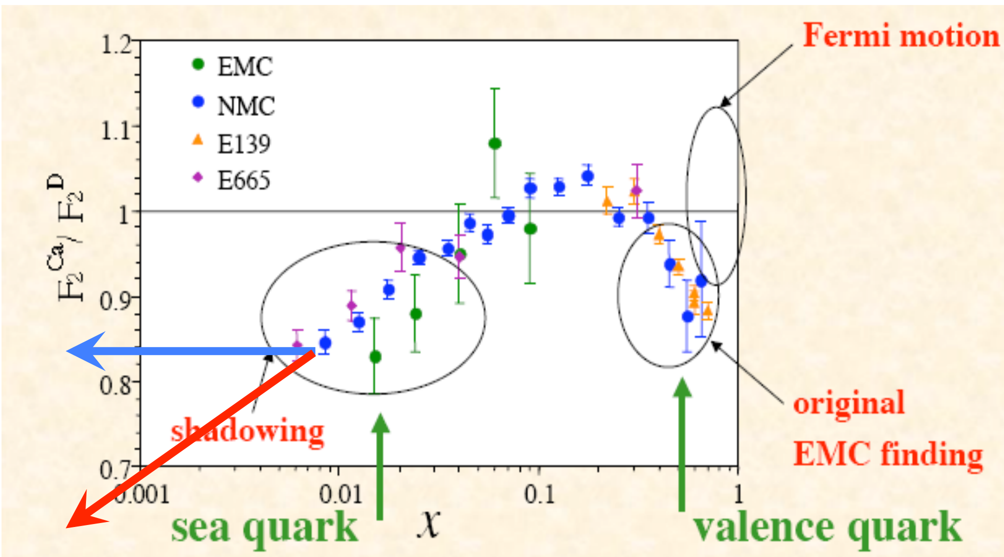
Independent tests of initial condition?

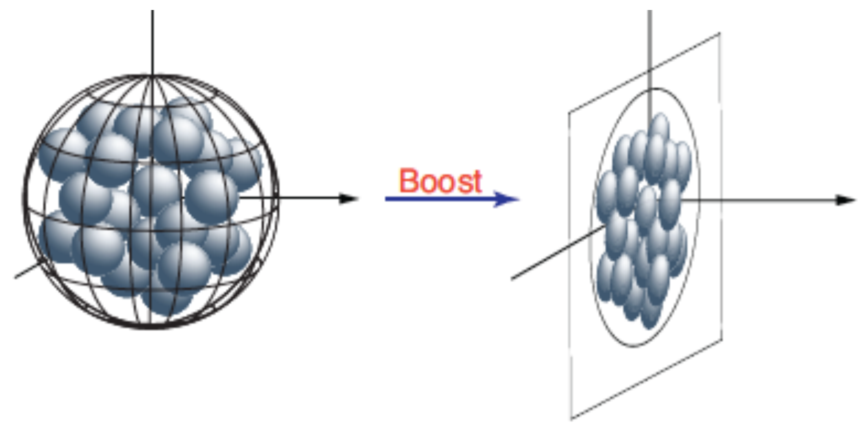
Nucleus – a QCD "molecule"

❑ The nucleus:

Binding energy/nucleon ~ 8 MeV << Q < a few GeV

❑ Surprise – EMC discovery:





✧ What is the nuclear landscape of see quarks and gluons?

Lump around the "nucleons"? QED: molecule/crystal
Quantum fluctuations?

✧ How does nuclear matter respond to a fast moving color charge?

Hadronization, nuclear matter as a filter? color tomography?

The question

How to meet these challenges and to answer these questions in QCD?

Critical to the nature of visible matter
Next frontiers of QCD and strong interaction!

Experimental tools

An Electron-Ion Collider (EIC)

Theoretical tools

Hard probes – Perturbative QCD and factorization

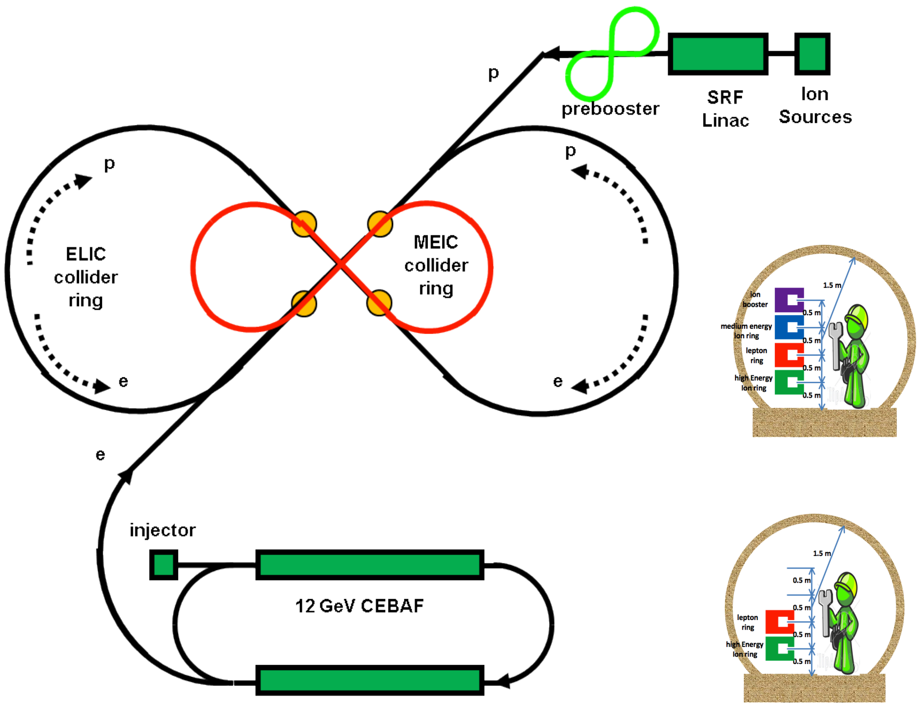
New effective d.o.f. – effective theory approaches

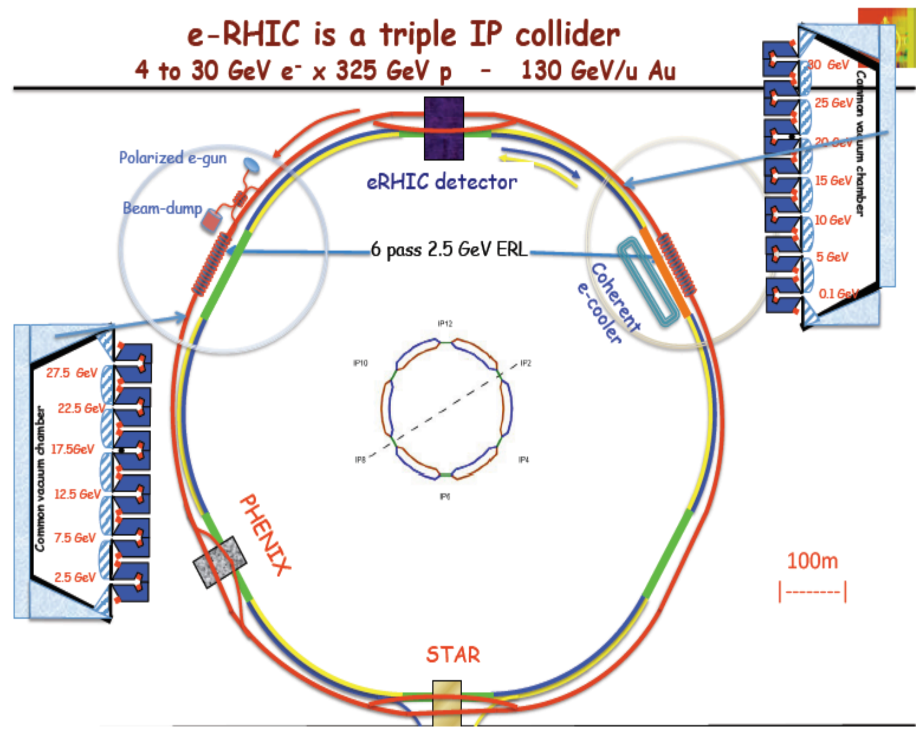
such as CGC and etc.

The US EIC proposals

- Two possible options:

ELIC (Jlab) **eRHIC (BNL)**





✧ First (might be the only) polarized electron-proton collider in the world

✧ First electron-nucleus (various species) collider in the world

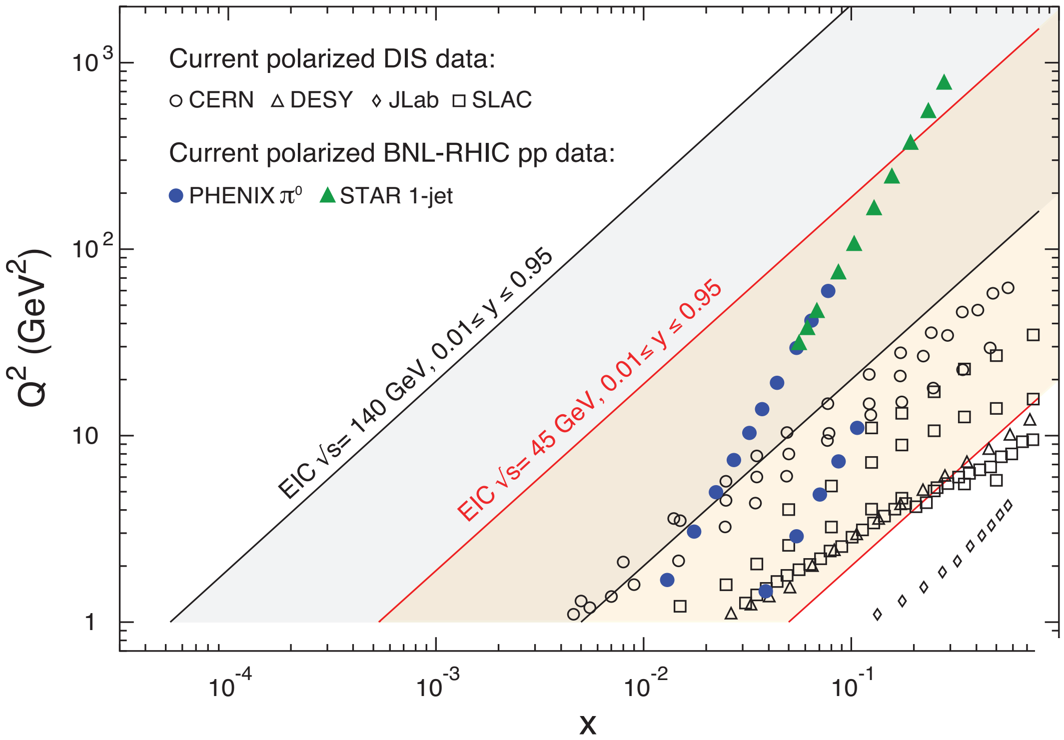
Staged realization:

Using existing facility

Stage I: $\sqrt{s}$ ~ 60-100 GeV

Stage II: $\sqrt{s}$ > 100 GeV

US EIC: Kinematics and properties

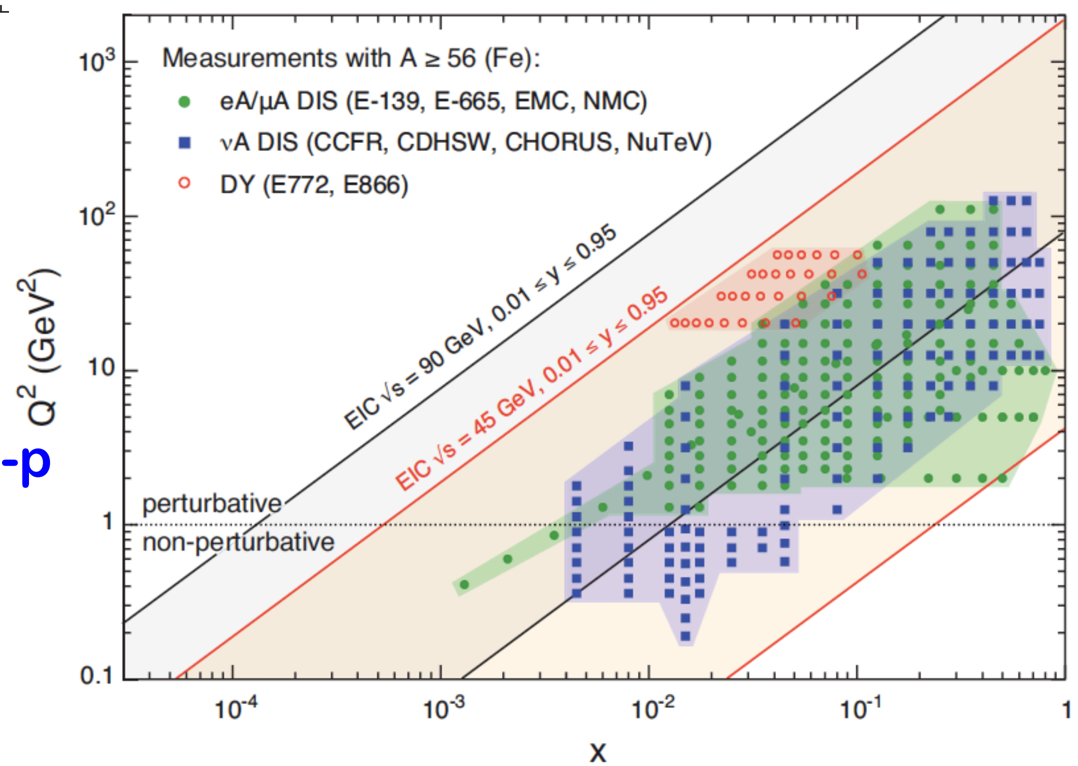


For e-N collisions at the EIC:

- ✓ Polarized beams: e, p, d, ^{3}He, …
- ✓ Luminosity $L_{ep} \sim 10^{33\text{-}34}$ cm^{-2}sec^{-1}
  100-1000 times HERA
- ✓ Variable center of mass energy

For e-A collisions at the EIC:

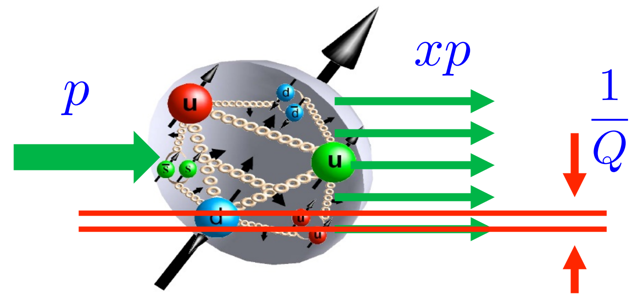
- ✓ Wide range in nuclei
- ✓ Luminosity per nucleon same as e-p
- ✓ Variable center of mass energy



What and why EIC can do and do better?

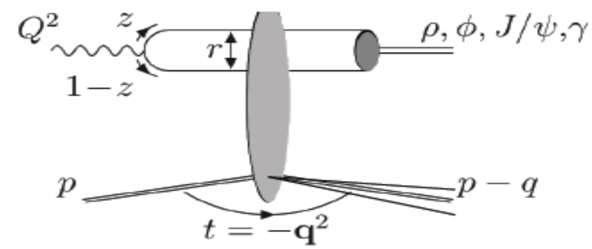
❑ High energy collider:

Sharper probe and better “snapshot” in probing the confined motion of quarks and gluons
– 3D momentum distributions



❑ High luminosity:

Diffractive scattering - CT scan the proton/nucleus
– 1+2D spatial imaging



- as a function of **t**

❑ Polarization:

$$\frac{\sigma(s)-\sigma(-s)}{\sigma(s)+\sigma(-s)}$$

Suppress probability – enhance quantum interference

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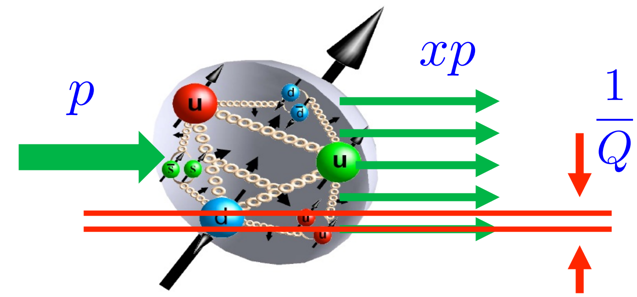

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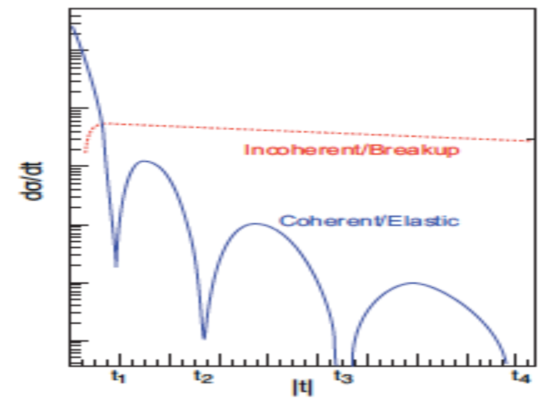


❑ Polarization:

$$\frac{\sigma(s)-\sigma(-s)}{\sigma(s)+\sigma(-s)}$$

Suppress probability – enhance quantum interference

❑ Nucleus, a QCD Laboratory:

✧ More soft gluons – Lab for exploring non-linear gluon dynamics

✧ Condensed color matter – Lab for QCD tomography

✧ Nuclear landscape – color confinement and quantum fluctuation

How a nucleus look if we only see quarks and gluons?

What an EIC can do?

Golden measurements
at
an Electron-Ion Collider

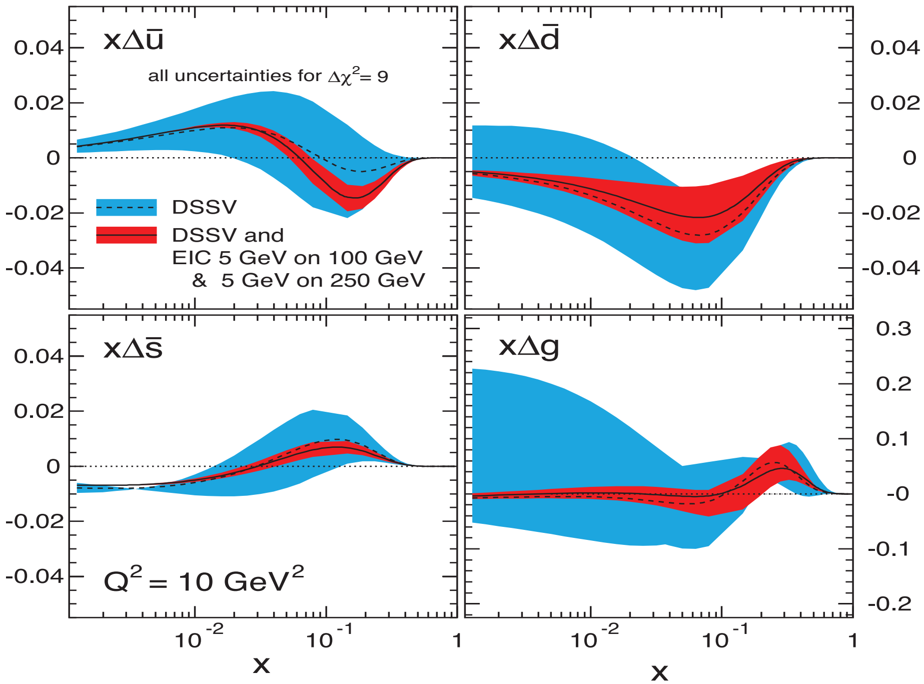
See also talks by
F. Yuan, Z. Xu, A. Deshpande
J.-P. Blaziot, K. Itakura
and others in connection to EIC

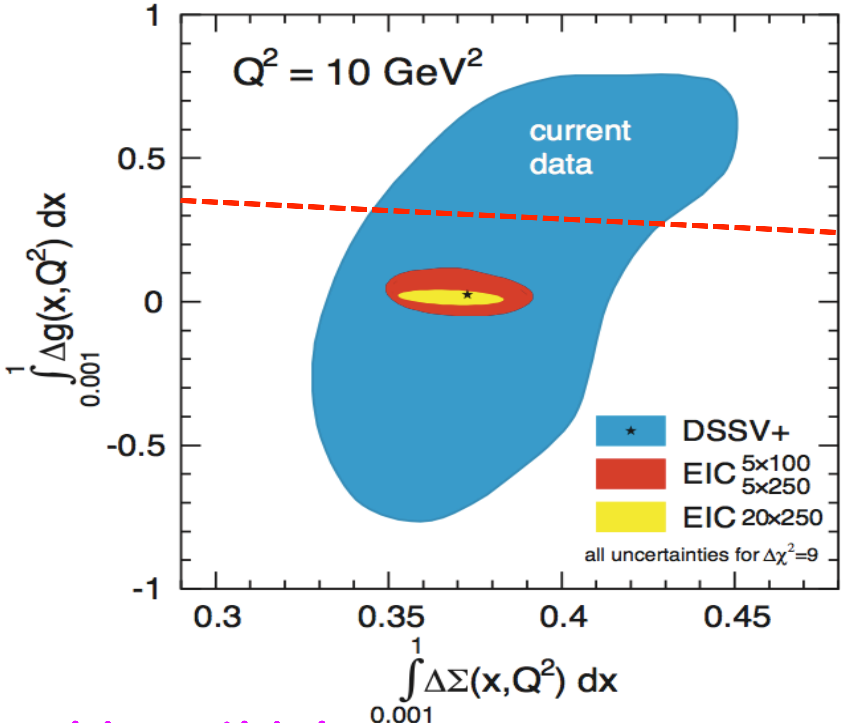
The spin and flavor structure of the nucleon

- Proton – composite particle of quarks and gluons:

  Spin = intrinsic (parton spin) + motion (orbital angular momentum)

- The EIC – the decisive measurement (two months running):





No other machine in the world can achieve this!

EIC White Paper

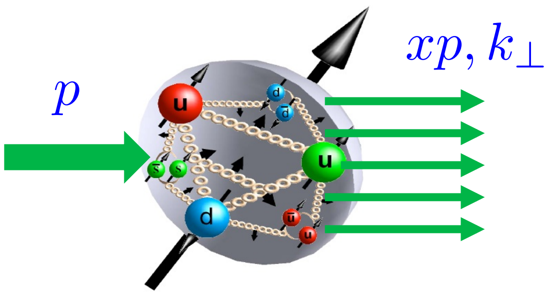
- The proton spin:

  Adding the Δg, is there still a deficit to the proton spin?

  If yes, we will have to investigate the orbital motion of quarks and gluons – the motion transverse to the proton's momentum

1+2D confined motion in a nucleon

- **Motion at the confining scale (<< Q) – partonic structure:**

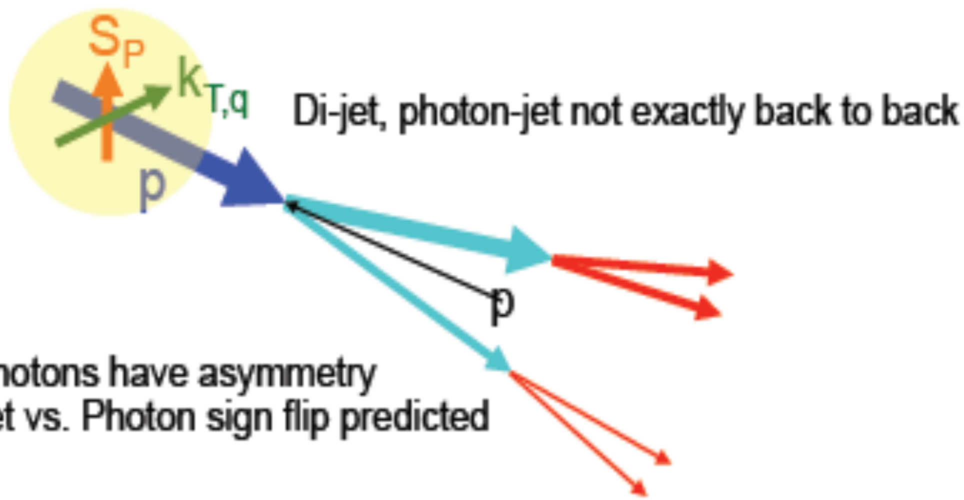


✧ **Transverse momentum dependent parton distributions (TMDs)**

✧ **Two scale observables: Q >> p_T ~ 1/fm**

✧ **Role of hadron and parton spin?**

- **Quantum correlation between hadron spin and parton motion:**



Sivers effect – Sivers function

Hadron spin influences parton's transverse motion

1+2D confined motion in a nucleon

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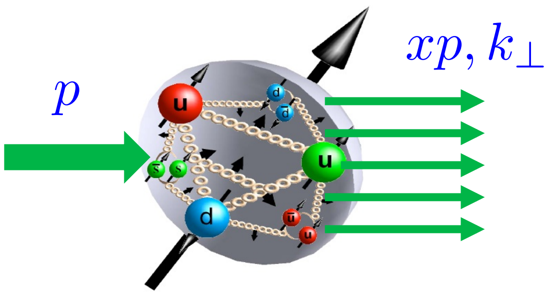

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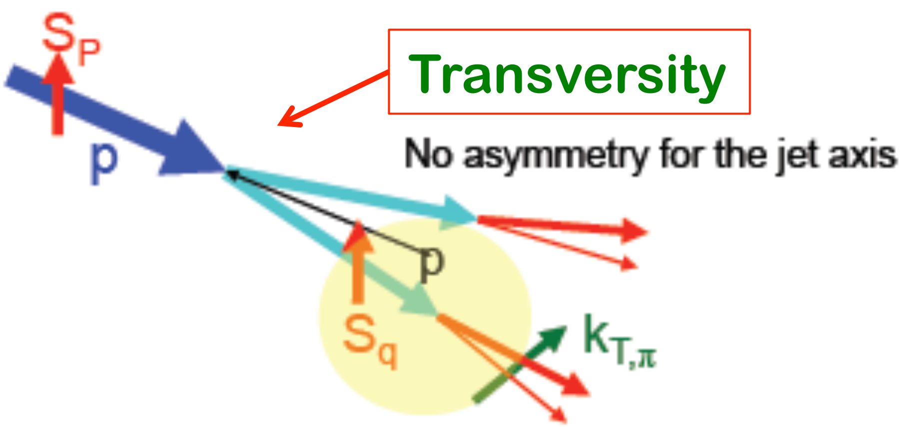


Collins effect – Collins function

Parton's transverse spin influence its hadronization

- **Single-spin asymmetry:**

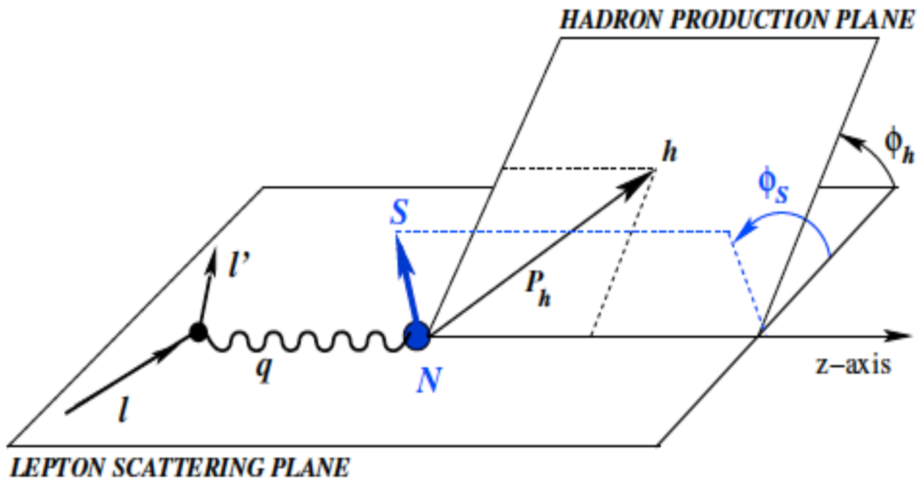
$$A(\ell,\vec{s}) \equiv \frac{\Delta\sigma(\ell,\vec{s})}{\sigma(\ell)} = \frac{\sigma(\ell,\vec{s})-\sigma(\ell,-\vec{s})}{\sigma(\ell,\vec{s})+\sigma(\ell,-\vec{s})}$$

Enhance the role of transverse motion – confined motion!

Only EIC can do this cleanly. Limitation on proton-proton machine

EIC is ideal for probing TMDs

❑ SIDIS – two scales and two scattering plans:



Two scales:

Q >> p_T (as well as Q ~ p_T)

Two scattering plans:

leptonic, and hadronic

❑ Angular modulations:

Natural separation of Collins effect from Sivers effect

$$A_{UT}(\varphi_h^l, \varphi_S^l) = \frac{1}{P}\frac{N^{\uparrow} - N^{\downarrow}}{N^{\uparrow} + N^{\downarrow}}$$

$$= A_{UT}^{Collins}\sin(\phi_h + \phi_S) + A_{UT}^{Sivers}\sin(\phi_h - \phi_S)$$

$$+ A_{UT}^{Pretzelosity}\sin(3\phi_h - \phi_S)$$

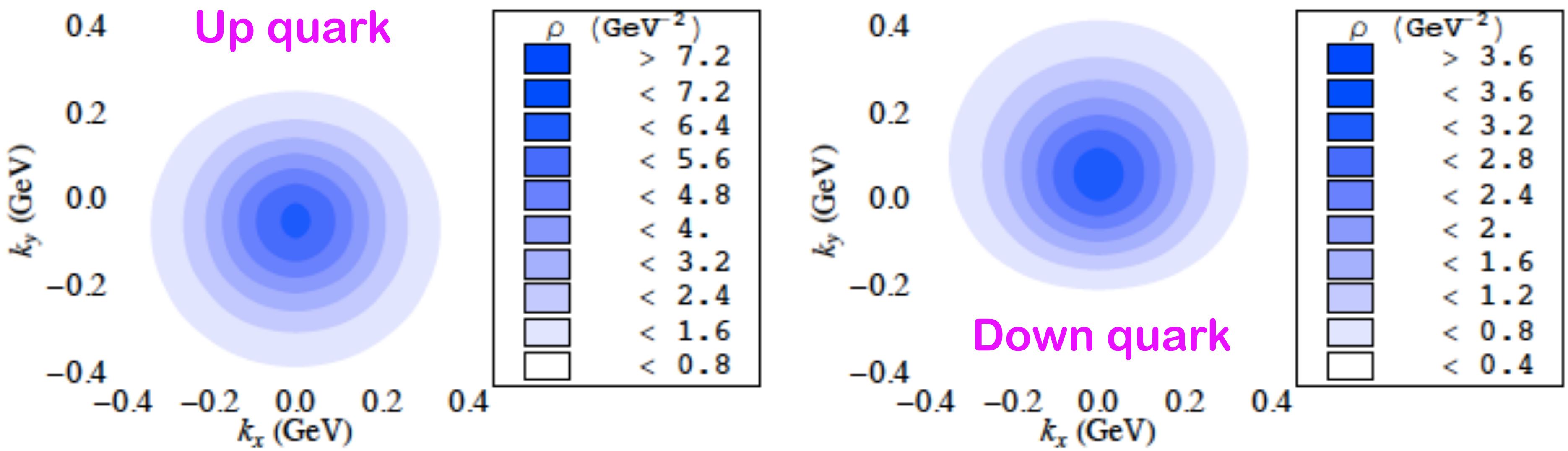
$$A_{UT}^{Collins} \propto \langle \sin(\phi_h + \phi_S) \rangle_{UT} \propto h_1 \otimes H_1^{\perp}$$

$$A_{UT}^{Sivers} \propto \langle \sin(\phi_h - \phi_S) \rangle_{UT} \propto f_{1T}^{\perp} \otimes D_1$$

$$A_{UT}^{Pretzelosity} \propto \langle \sin(3\phi_h - \phi_S) \rangle_{UT} \propto h_{1T}^{\perp} \otimes H_1^{\perp}$$

What EIC can do to Sivers function?

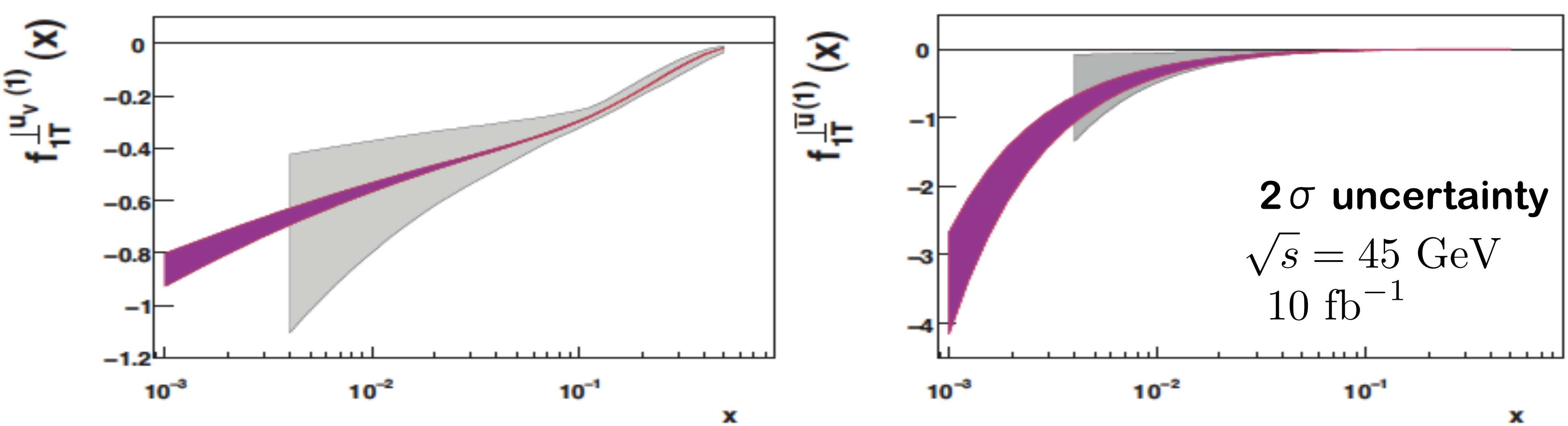
- Unpolarized quark inside a transversely polarized proton:



EIC White Paper

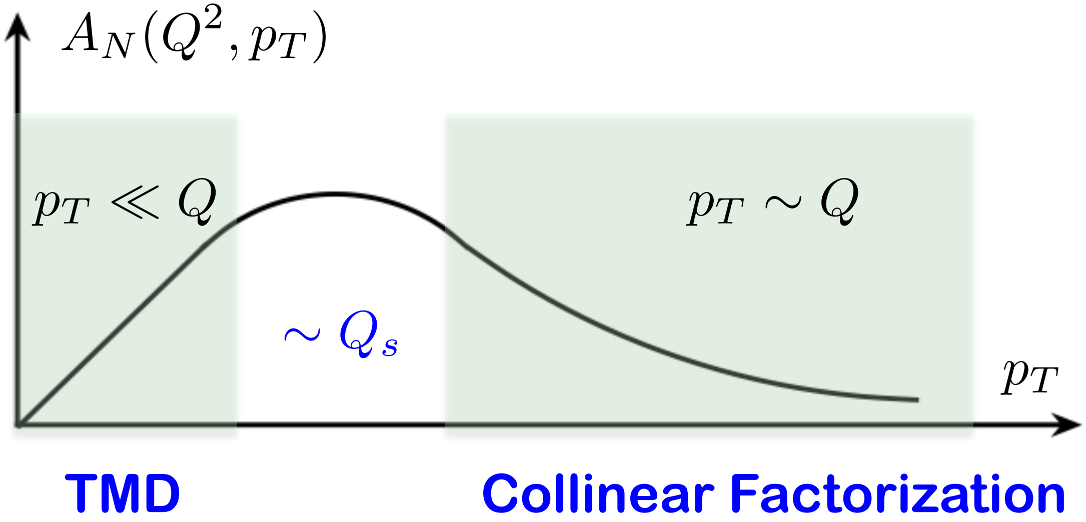
Color confined radius at different x?

- Role of momentum fraction – x:



Transition from low p_T to high p_T

❑ **TMD factorization to collinear factorization:**



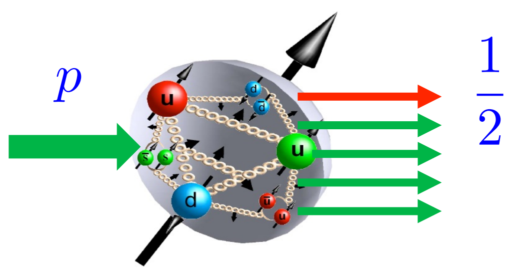
Two factorization are consistent in the overlap region where

$$\Lambda_{\rm QCD} \ll p_T \ll Q$$

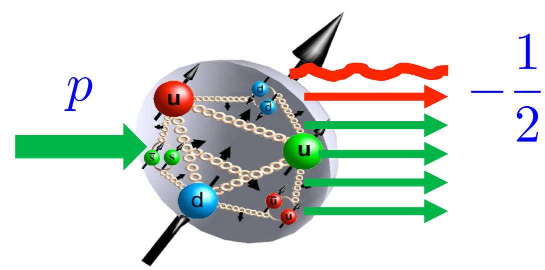
❑ **Quantum interference – high p_T region (integrate over all k_T):**

Single quark state

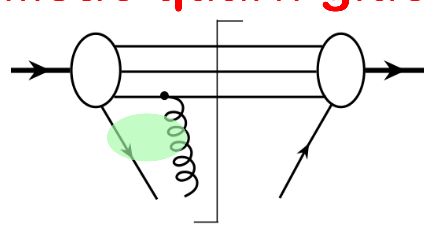
quark-gluon composite state



interfere with (Spin flip)



→ Non-probabilistic quark-gluon quantum correlation

$T^{(3)}(x,x) \propto$ 

Expectation of color Lorentz force

See J.P. Ma's talk

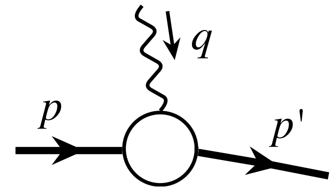
1+2D spatial imaging of color?

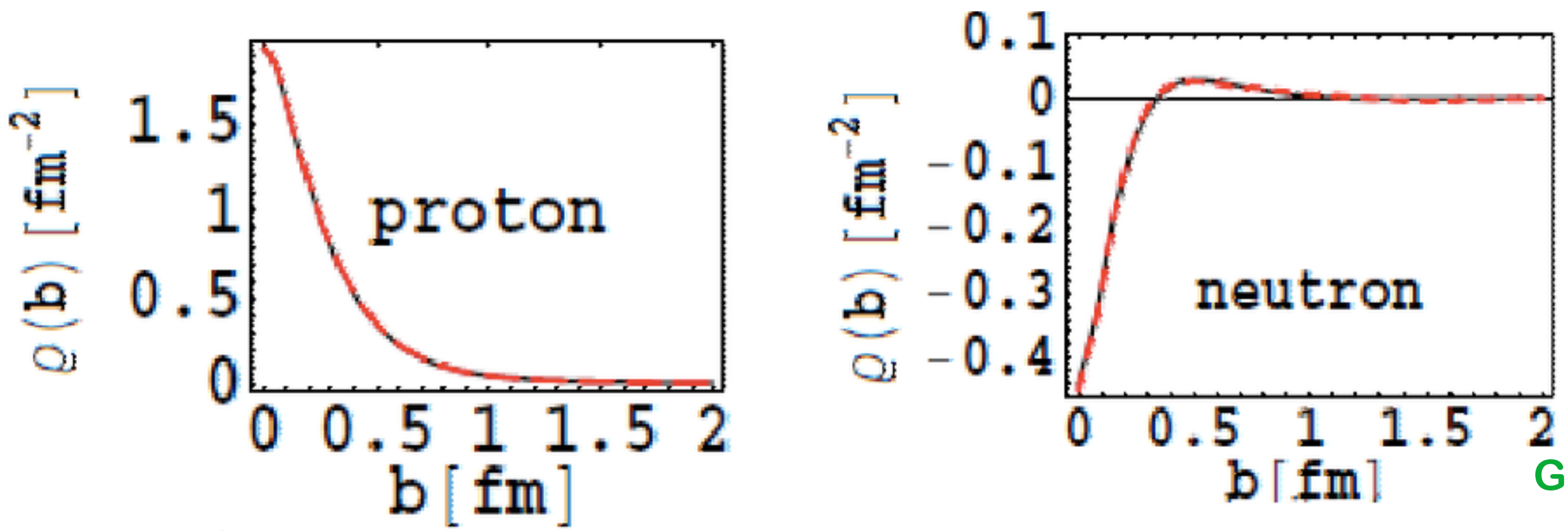
- The "big" question:

  How color is distributed inside a hadron? (clue for color confinement?)

- Electric charge distribution:

  Elastic electric form factor ⟹ Charge distributions

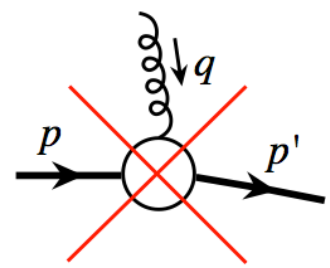




G.A. Miller (2007)

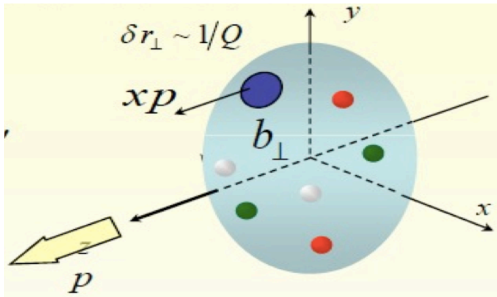
- But, NO color elastic nucleon form factor!

  Hadron is colorless and gluon carries color

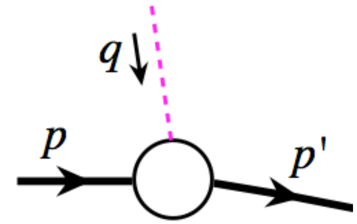


1+2D spatial parton density

- Partonic structure – spatial distributions of quarks and gluons:

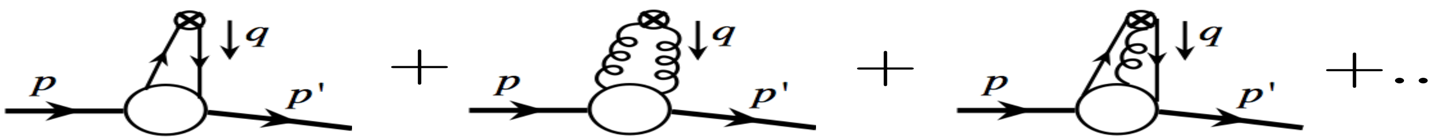


- ✧ Need a localized probe
- ✧ Scan in transverse direction
- ✧ Partonic structure



Exchange of colorless object

- Need exclusive processes – diffractive scattering

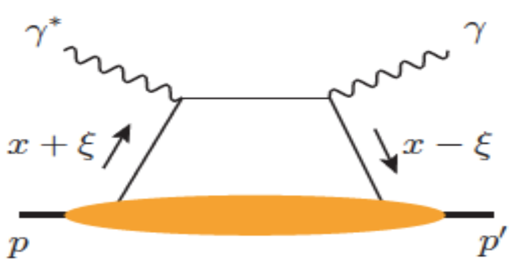


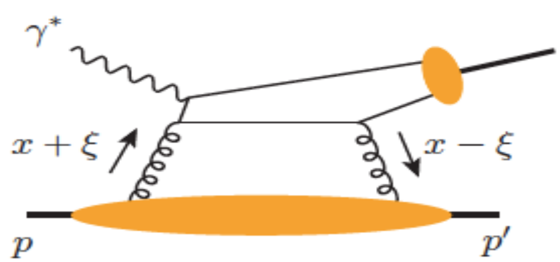
But, every parton can participate – need a “localized” probe!

EIC at high energy can provide large Q, phase-space for t = $(p'-p)^2$!

No factorization for hadron-hadron diffractive scattering !

- Deep virtual Compton Scattering (DVCS):





$$\frac{d\sigma}{dx_B dQ^2 dt}$$

$$\Delta = p' - p$$

$$t = (p' - p)^2$$

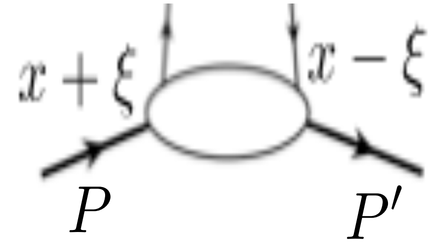
Generalized parton distributions (GPDs)

- **Quark "form factor":**

$$F_q(x,\xi,t,\mu^2) = \int \frac{d\lambda}{2\pi} e^{-ix\lambda} \langle P' | \bar{\psi}_q(\lambda/2) \frac{\gamma\cdot n}{2P\cdot n} \psi_q(-\lambda/2) | P\rangle$$

$$\equiv H_q(x,\xi,t,\mu^2)\,[\bar{\mathcal{U}}(P')\gamma^\mu \mathcal{U}(P)]\,\frac{n_\mu}{2P\cdot n}$$

$$+\; E_q(x,\xi,t,\mu^2)\left[\bar{\mathcal{U}}(P')\frac{i\sigma^{\mu\nu}(P'-P)_\nu}{2M}\mathcal{U}(P)\right]\frac{n_\mu}{2P\cdot n}$$



with $\xi = (P'-P)\cdot n/2$ and $t = (P'-P)^2 \Rightarrow -\Delta_\perp^2$ if $\xi \to 0$

$\tilde{H}_q(x,\xi,t,Q)$, $\tilde{E}_q(x,\xi,t,Q)$ **Different quark spin projection**

- **Total quark's orbital contribution to proton's spin:** Ji, PRL78, 1997

$$J_q = \frac{1}{2}\lim_{t\to 0}\int dx\, x\,[H_q(x,\xi,t) + E_q(x,\xi,t)]$$

$$= \frac{1}{2}\Delta q + L_q$$

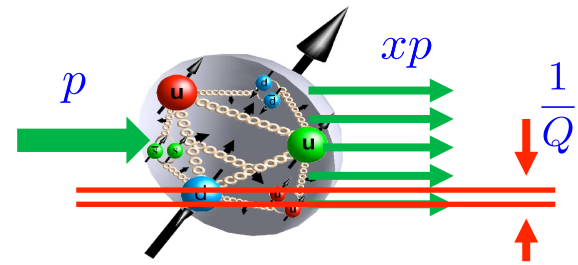
- **Connection to normal quark distribution:**

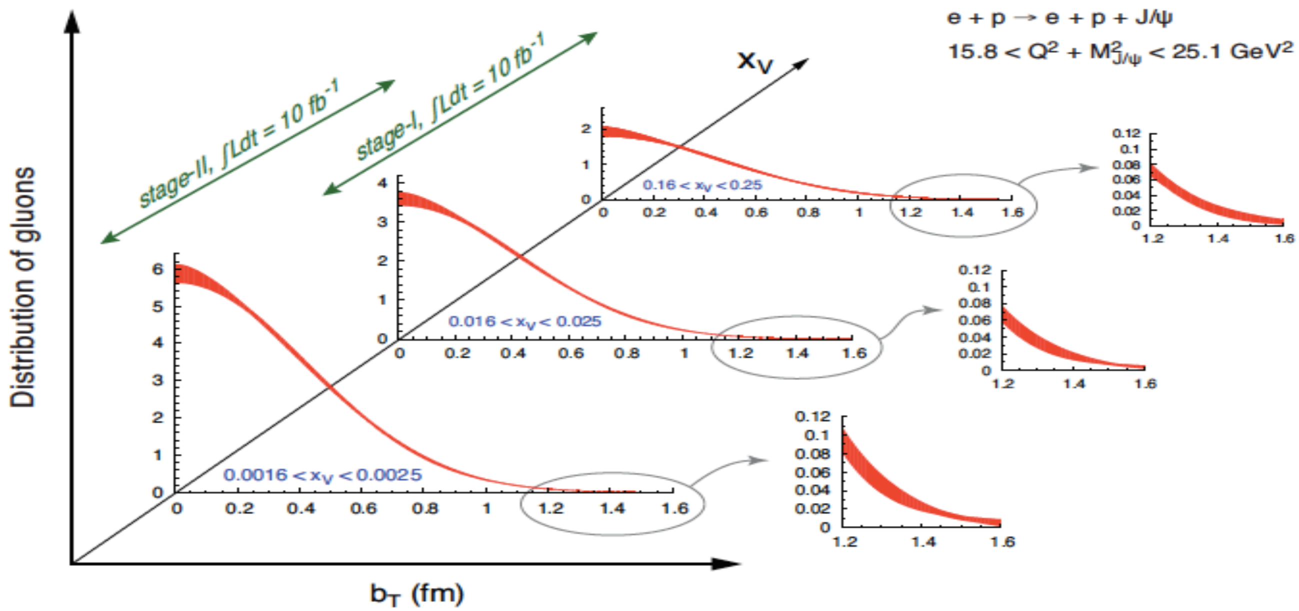
$$H_q(x,0,0,\mu^2) = q(x,\mu^2)$$ **The limit when** $\xi \to 0$

1+2D spatial imaging of parton density

❑ 2D Fourier transformation:

$$q(x, |\vec{b}|, Q^2) = \frac{1}{4\pi} \int_0^\infty d|t|\, J_0(|\vec{b}|\sqrt{|t|})\, H(x, \xi = 0, t, Q^2)$$





Images of gluons from exclusive J/Psi production

Only at an EIC

EIC White Paper

❑ Quark GPDs and its orbital contribution to proton's spin:

$$J_q = \frac{1}{2} \lim_{t\to 0} \int dx\, x\, [H_q(x,\xi,t) + E_q(x,\xi,t)] = \frac{1}{2}\Delta q + L_q$$

The first meaningful constraint on quark orbital contribution to proton spin by combining the sea from the EIC and valence region from JLab 12

Should this be consistent with Lattice QCD?

Lattice calculation on parton orbital motion

Negele et al

- Moments of GPDs on lattice:

$$\langle J_q^i \rangle = S^i \int dx \left[H_q(x,0,0) + E_q(x,0,0) \right] x$$

- Ji's relation:

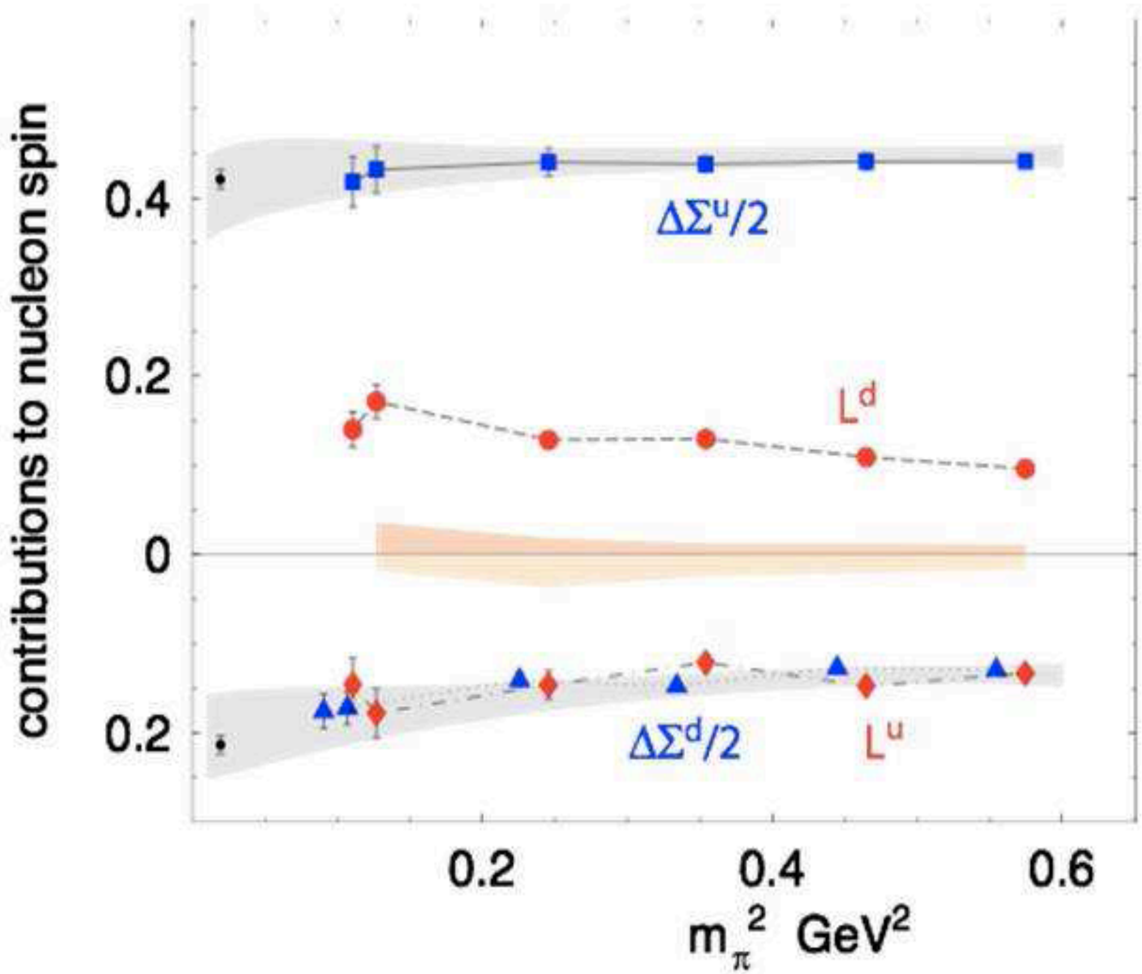
$$L_q^z = J_q^z - \frac{1}{2}\Delta q$$

- Both L_u and L_d large:

But, $L_u + L_d \sim 0$

- Spin from the gluon?

EIC is an ideal place
to measure gluon GPDs
From QCD evolution and
diffractive J/ψ



Nucleus, a Laboratory for QCD

- The nucleus:

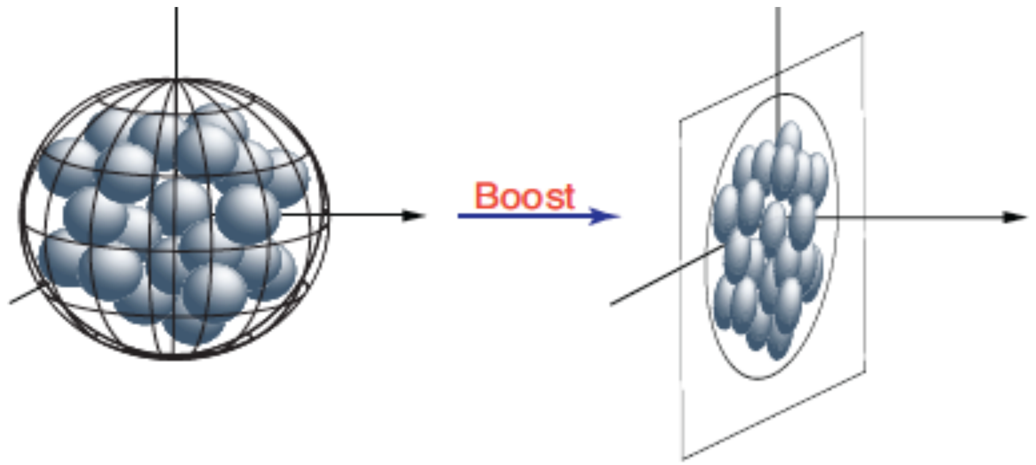
  Binding energy/nucleon ~ 8 MeV << Q < a few GeV

  Nuclear landscape = superposition of nucleon landscape

- EMC effect:

  Nuclear landscape =\= superposition of nucleon landscape

- "Snapshot" does not have a "sharp" depth at small x_B



Probe size: transverse - $\frac{1}{Q} \ll 1\ \mathrm{fm}$, longitudinal size - $\frac{1}{xp} \sim \frac{1}{Q} \ll 1\ \mathrm{fm}$

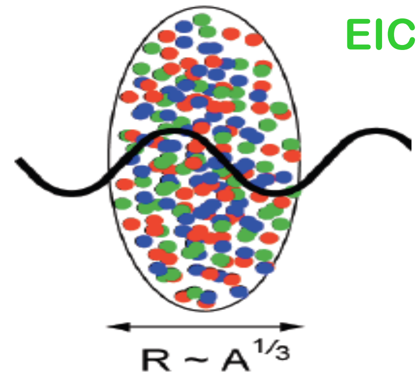
Longitudinal size > Lorentz contracted nucleon: $\frac{1}{xp} > 2R\frac{m}{p}$

$$x < x_c = \frac{1}{2mR} \sim 0.1$$

Reaching the saturation with eA

- Many more soft gluons in nucleus at the same impact parameter:

$$Q_s^2(eA) \propto Q_s^2(ep)\ A^{1/3}$$



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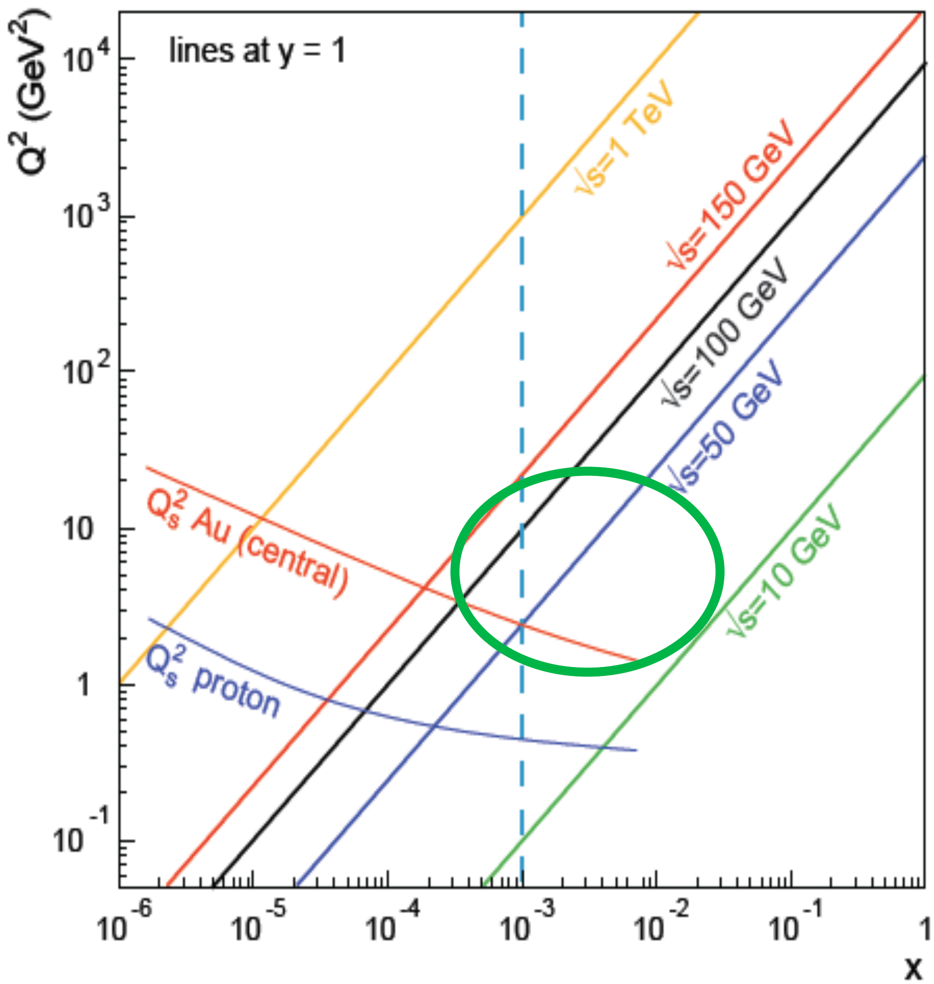
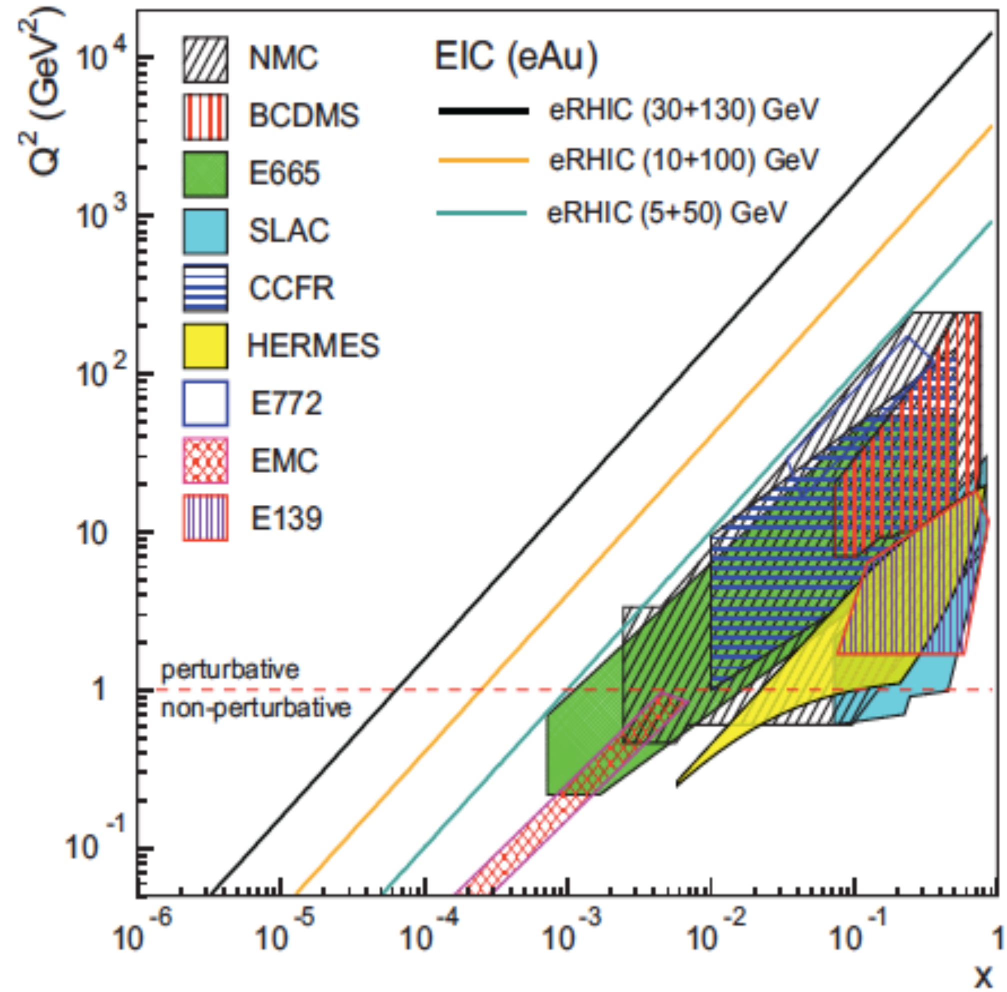
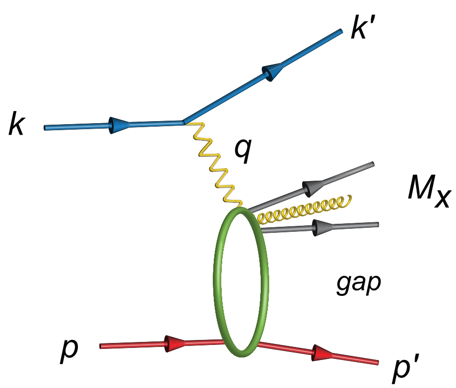




Saturation/CGC: What to measure?

- **Inclusive events – structure functions, F_2 and F_L:**
  - High energy – smaller x, and larger range of Q^2
  - Search for deviation from DGLAP and BFKL

- **Diffractive cross section:**



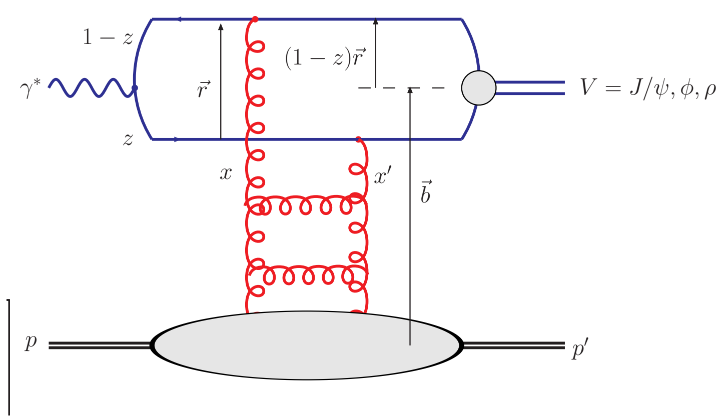
$$\sigma_{\mathrm{diff}} \propto \left[g(x,Q^2)\right]^2$$

At HERA: ep observed 10-15%/total

If CGC/Saturation – multiple coherent gluons

→ Diffraction eA expect ~25-30%/total

- **Diffractive vector meson production:**

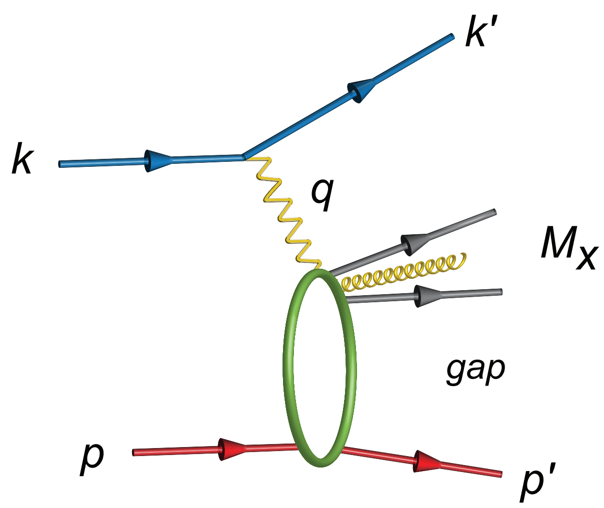


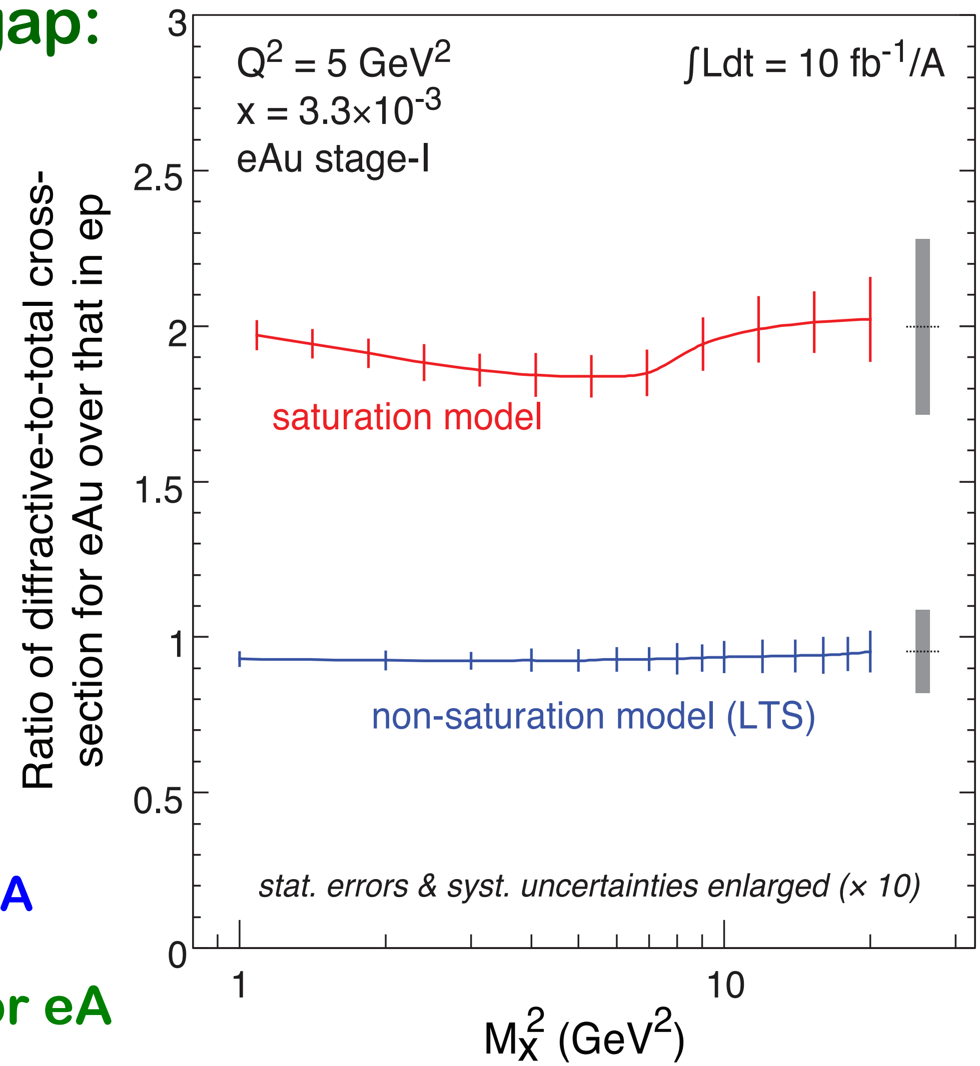
Cross section ratio for eA/ep: J/Ψ and φ

→ Very different behaviors predicted for J/Ψ and φ (different transverse size)

Diffractive over total cross section

❑ Hard scattering with a rapidity gap:





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✧ Color singlet exchange,
strong non-linear effect

✧ Factorization works in DIS, not in pp, pA, AA

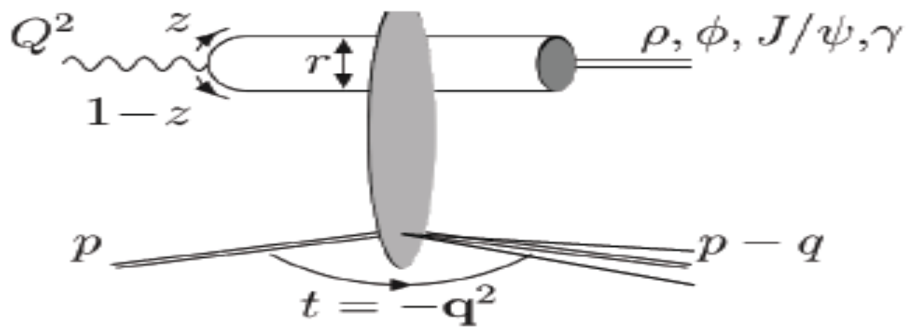
The factor of 2 enhancement is only for eA
(no equivalent in pA!)

This is a clean and unambiguous signal of saturation physics
already at EIC stage-1

Special imaging of the nucleus

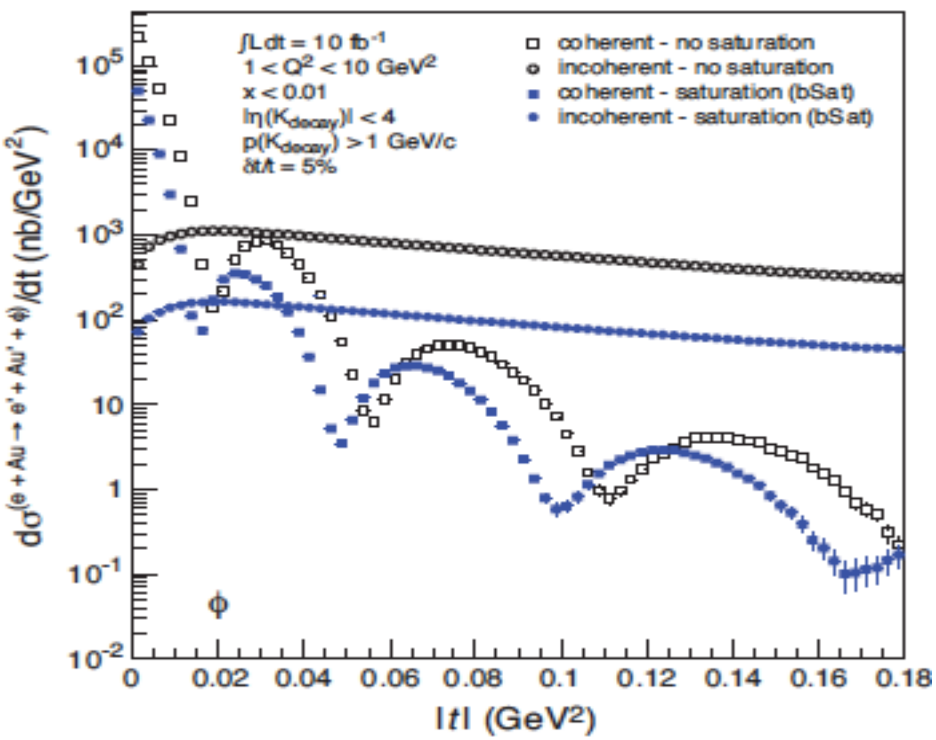
- ❑ **Diffractive vector mesion (Φ, J/ψ, ..) production:**

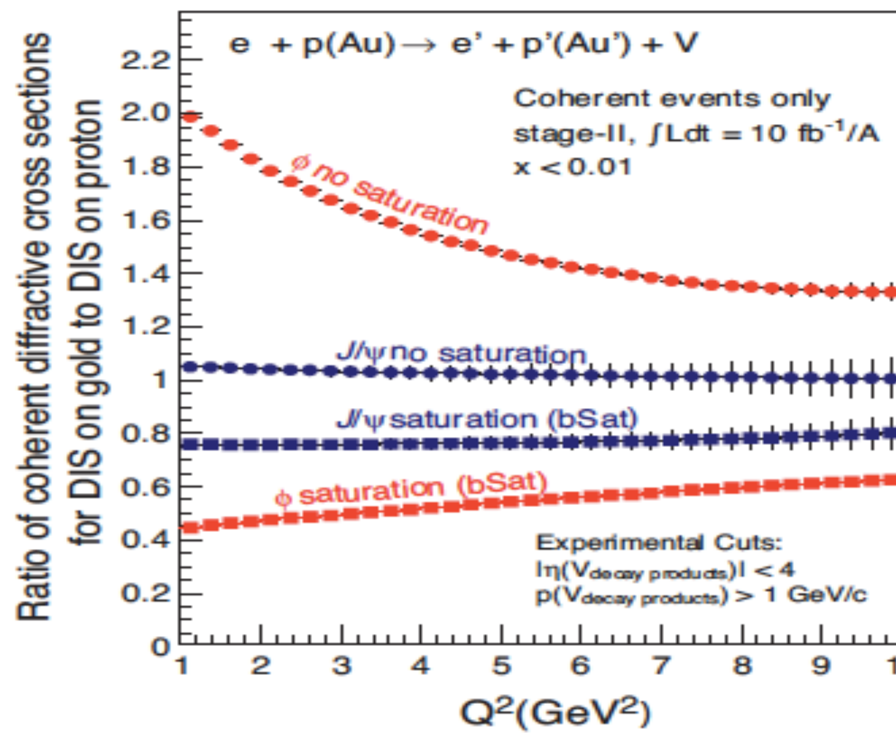
EIC White Paper



- as a function of **t**

- ❑ **Φ–production – clean probe for spatial distributions:**

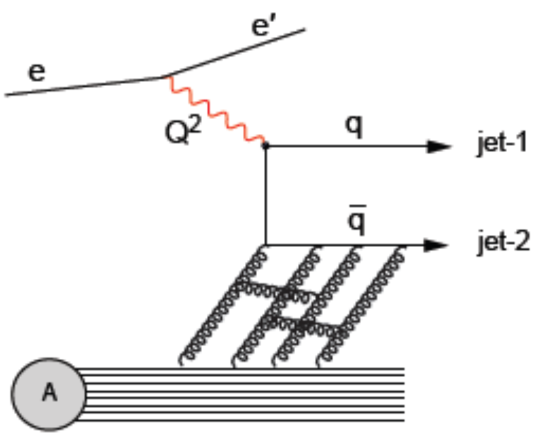




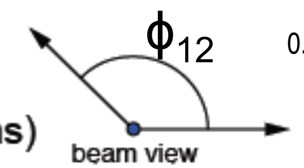
Di-hadron angular distributions at an EIC

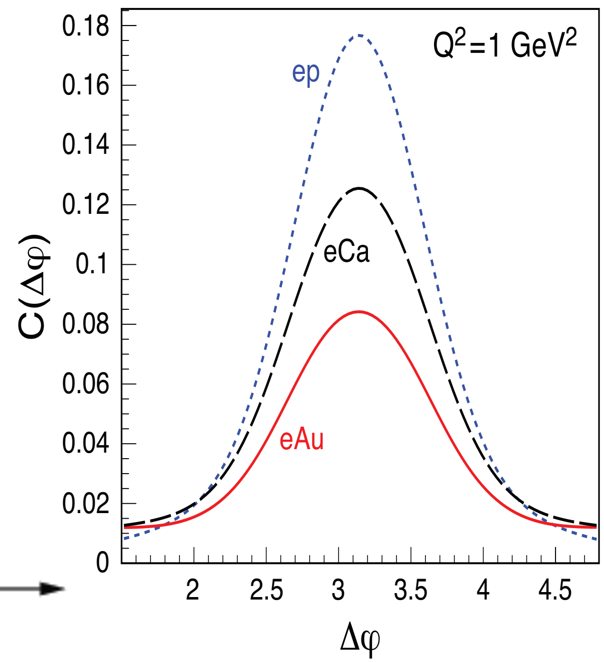
Dominguez, Xiao, Yuan (2010)

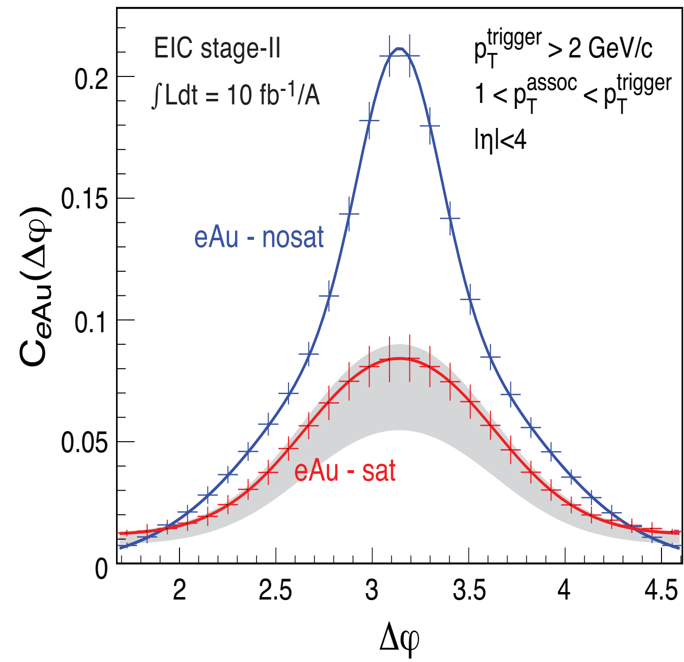
- Strong suppression of dihadron correlation in eA:



Either Jets or use leading hadrons from jets (dihadrons)







- Never be measured!
- Directly probe Weizsacker-Williams (saturated) gluon distribution in a large nucleus – not the normal dilute gluon distribution!
- A factor of 2 suppression of away-side hadron-correlation!

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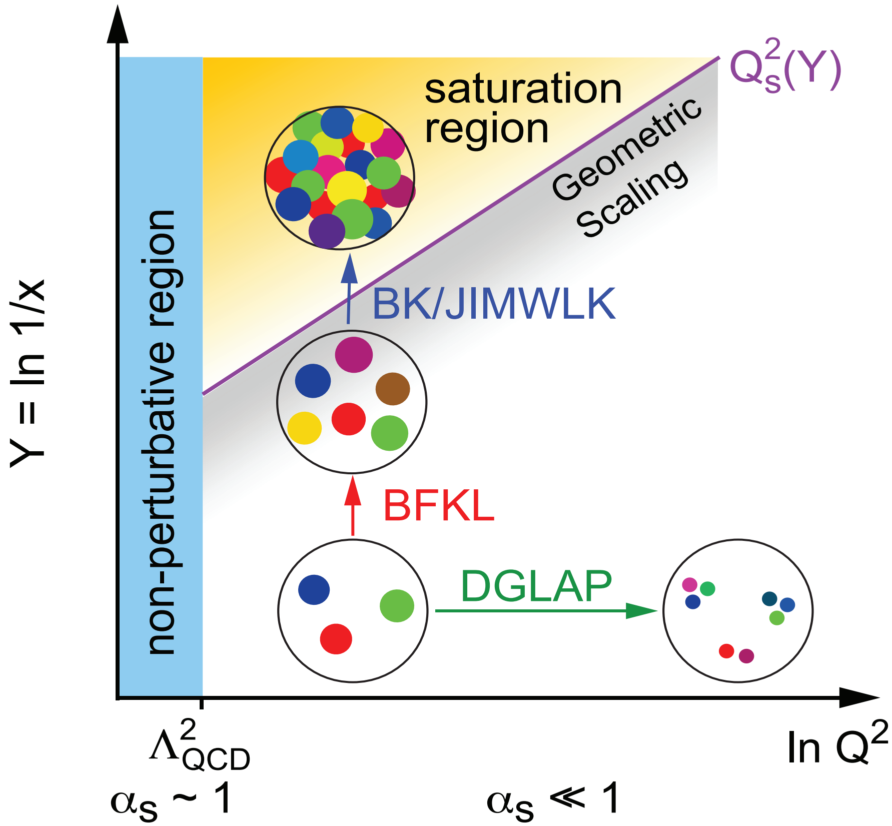
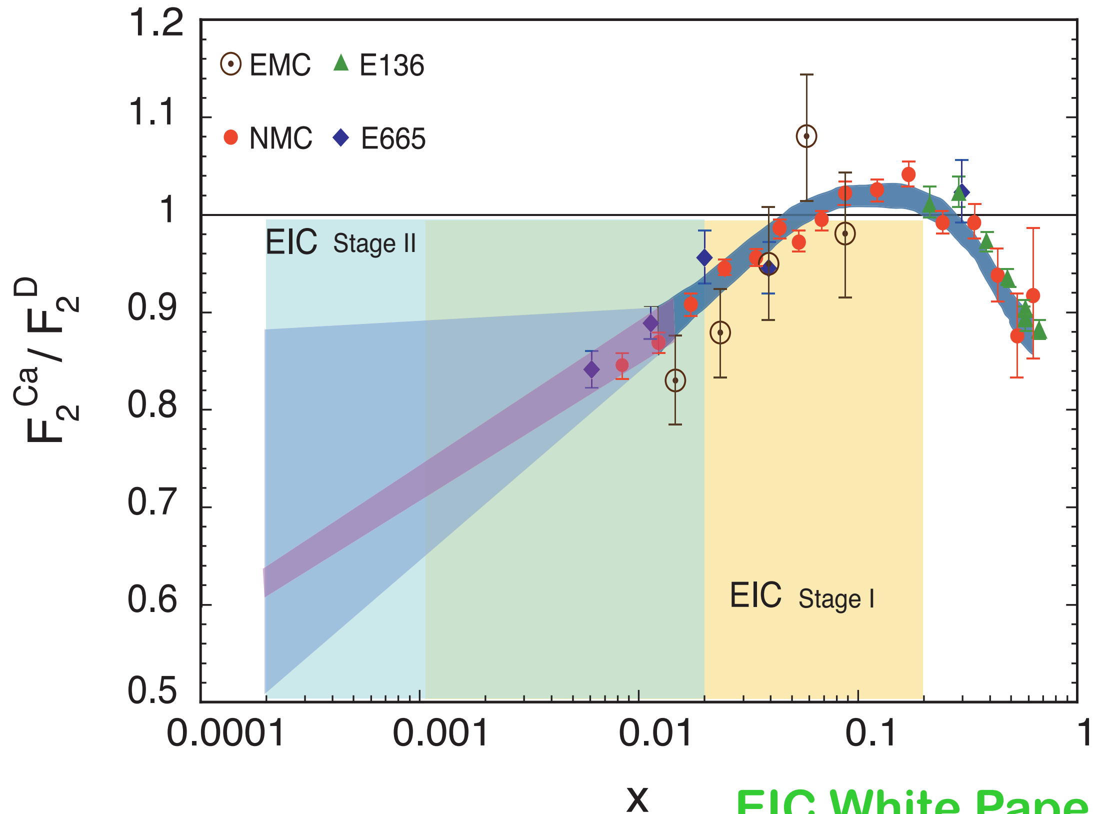
Nuclear parton distributions

❑ **The EICs are ideal for exploring the transition region:**

Cross section: $0.0001 < x < 0.1$, $1\ \mathrm{GeV}^2 < Q^2$ ⟶ DIS structure functions





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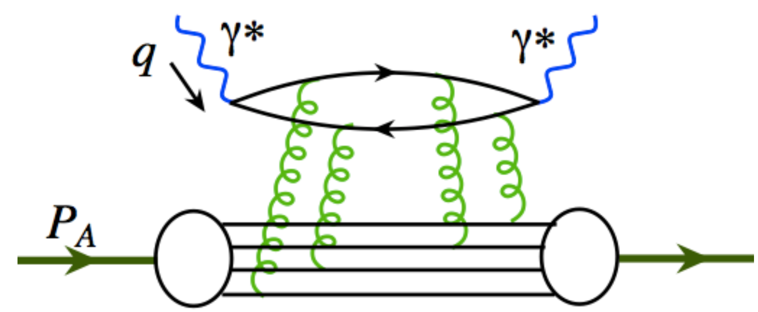
✧ **Saturation of the ratio for x > 0.001 =\= saturation of nuclear structure function**

✧ **Color confinement length in nuclei?**

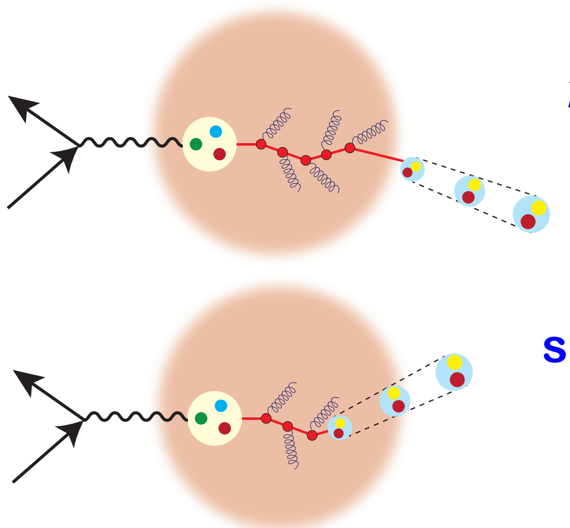
Nucleon size – top of the shade area?

Nuclear size – bottom of the shade area?



Hadronization – energy loss

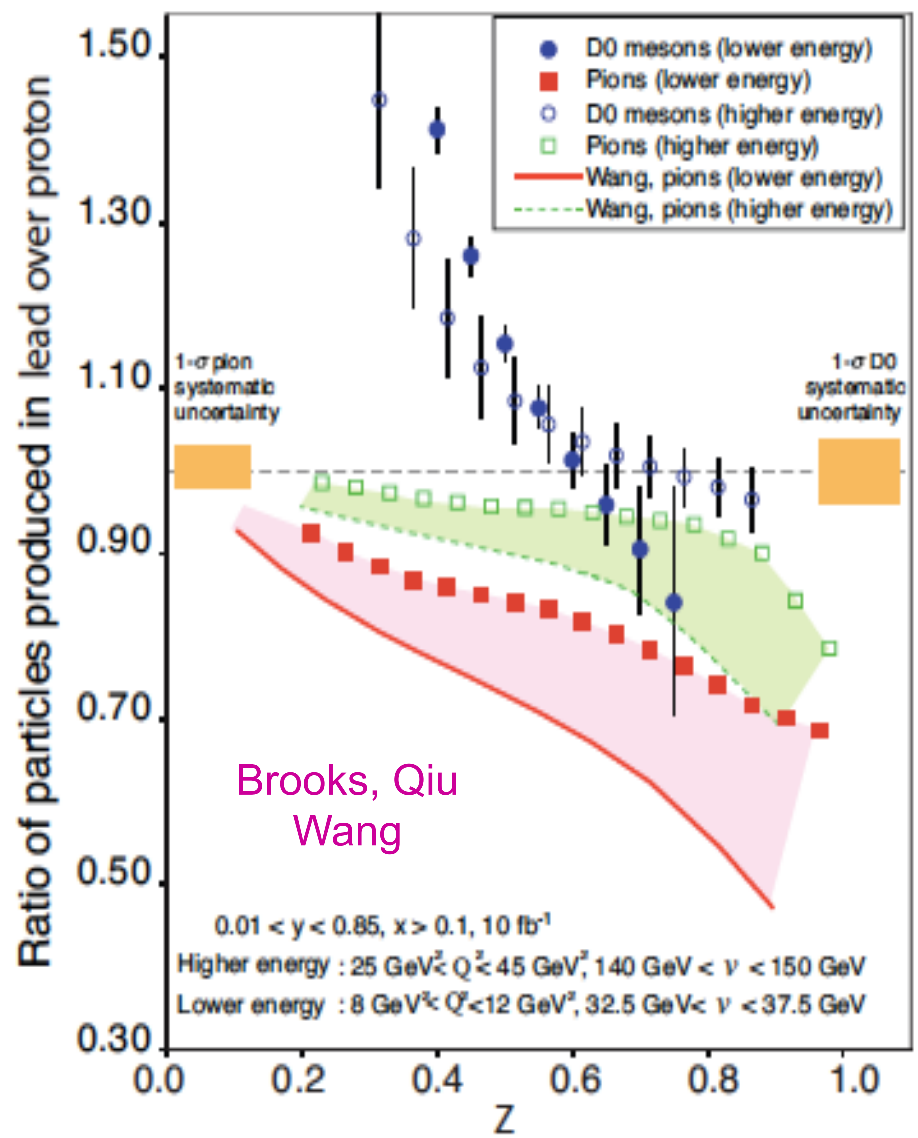
❑ Unprecedented ν range at EIC:



$$\nu = \frac{Q^2}{2mx}$$

semi-inclusive DIS

- ✧ **Small ν - in medium hadronization:**
  - dynamics of confinement
  - stages of hadronization and their time scales
- ✧ **Large ν - parton multiple scattering:**
  - Parton propagation in medium
  - Energy loss and broadenning, $\hat{q}$
  - Direct access to fragmentation



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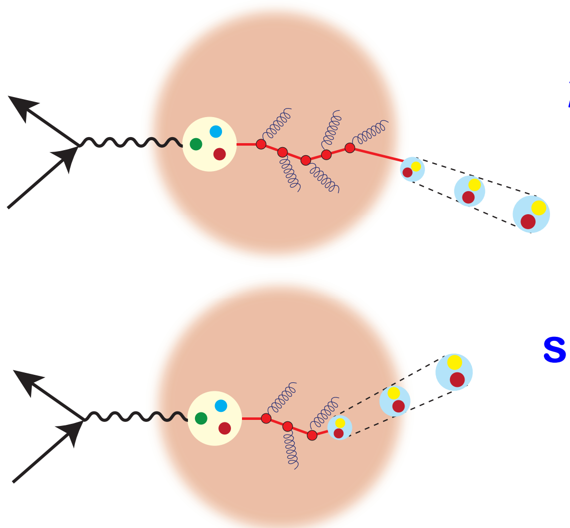
Hadronization – energy loss

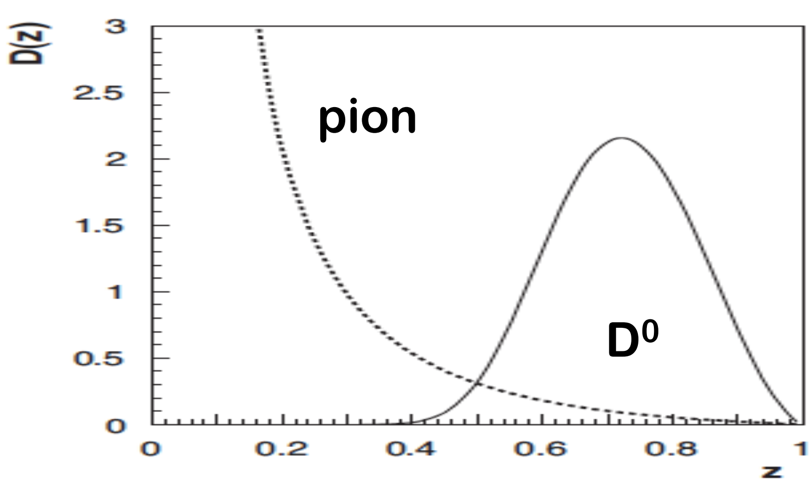
- Unprecedented ν range at EIC:

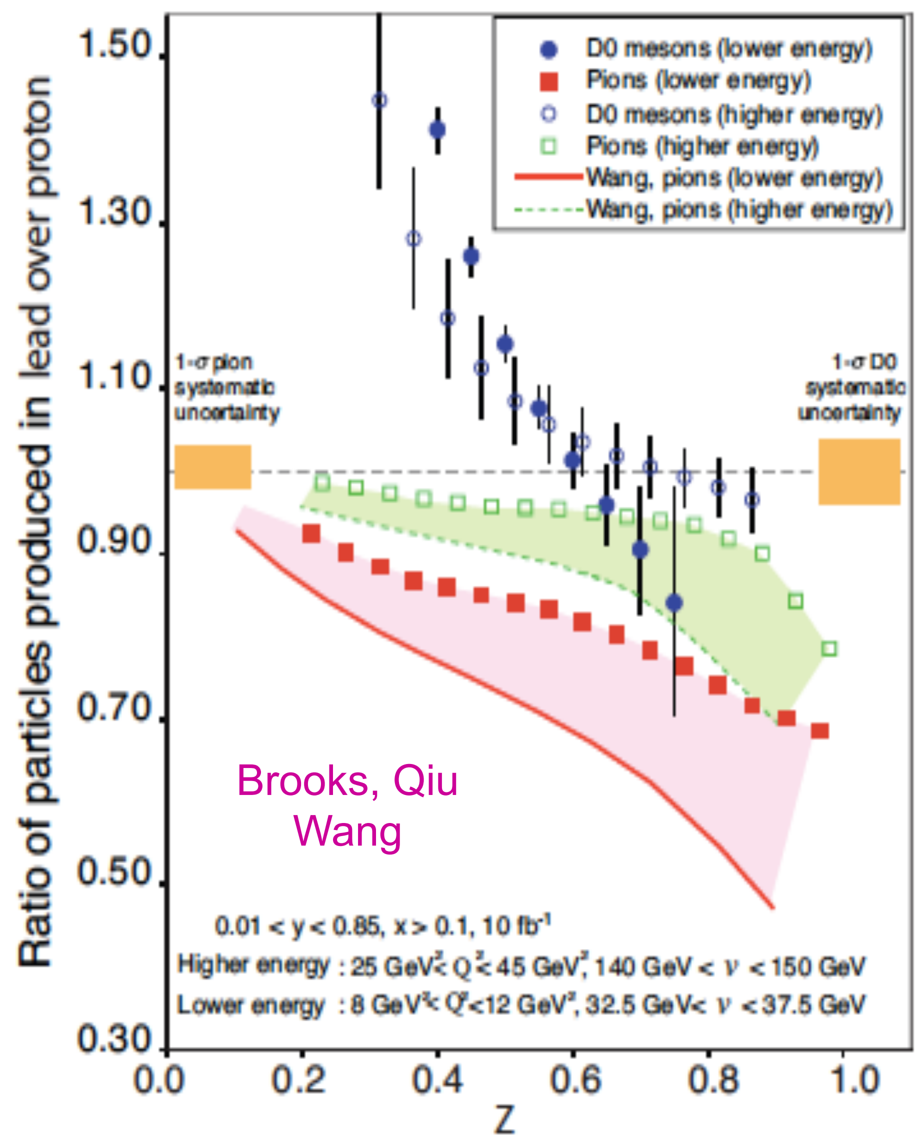


$$\nu = \frac{Q^2}{2mx}$$

semi-inclusive
DIS

- First time access to heavy quarks
  - Mass dependance of fragmentation





Need the collider energy of EIC

EIC White Paper

Summary

- After almost 40 years, we have learned a lot of QCD dynamics, but, only in its most trivial asymptotic regime (less than 0.1 fm), and very limited information on nucleon/nuclear structure

- Many aspects of hadron's partonic structure can be naturally addressed by EIC, but, not other machines: e+e-, pp, pA, AA

- EIC with polarization provides a new program to explore new frontier research of QCD dynamics – key to the visible matter

Rutherford exp't	SLAC "Rutherford"	Future "Rutherford"
1911	1969	2020?
Nucleus Atomic structure	Parton Collinear PDFs	Many body non-linear dynamics Confined partonic structure

See also talks by F. Yuan, A. Deshpande, and others on EIC

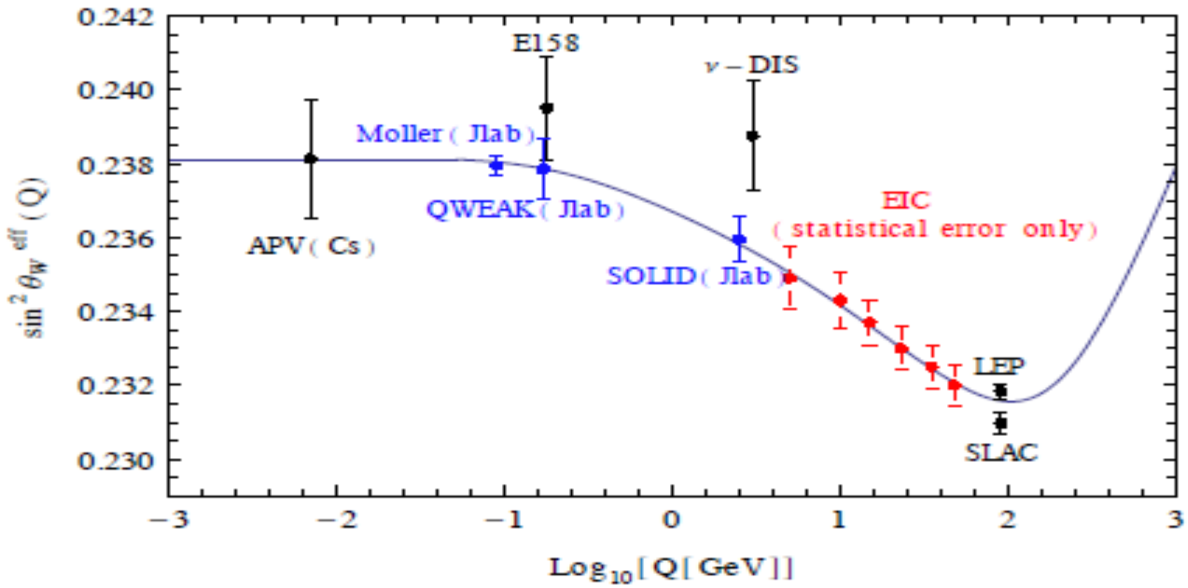
Thanks!

Three most important stage-I goals of EIC

- ❑ Extract the confined motion of quarks and gluons in a nucleon with and without polarization, and in a nucleus
  - ✧ Possible clue for color confinement, hadron – parton correlations, …
  - ✧ Ultimate solution of proton spin – hadron property in QCD
  - ✧ Naturally measured at EIC, not easy, if not impossible, at other machines
- ❑ Measure the confined spatial distribution of quarks and gluons in a nucleon with and without polarization, and in a nucleus
  - ✧ Complementary to the motion measurement
  - ✧ Sum rule for proton spin – hadron property in QCD
  - ✧ EIC has the "sufficient" kinematic reach for reliable imaging
- ❑ Discover clear evidences of QCD's many body non-linear dynamics and the range of color coherence
  - ✧ Saturation scale – consequence of QCD non-linear dynamics
  - ✧ Range of color coherence – nuclear property in QCD
  - ✧ EIC, like RHIC for heavy ion, can pioneer the search of non-linear dynamics

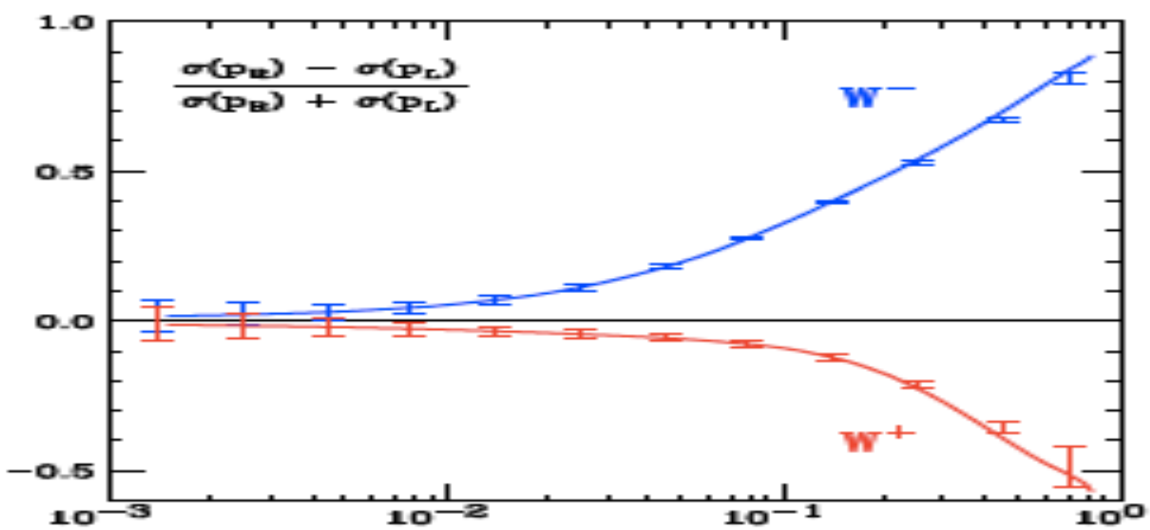
Electroweak physics at EIC

- ❑ **Mixing angle of weak interaction – high luminosity:**



Fill the region never be measured

- ❑ **Parity-violating single longitudinal asymmetries:**



Flavor separation of helicity distributions

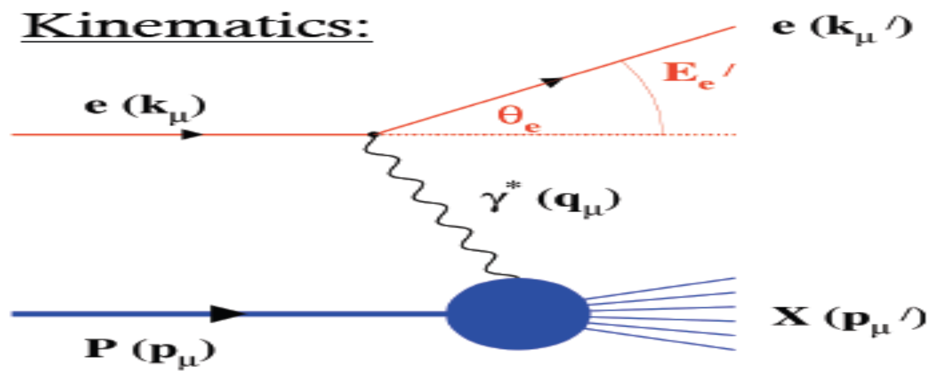
Probes – taking "snap short" at EIC

- **Inclusive (1 hard scale):**

  1-D momentum distributions

  $$q(x,Q), G(x,Q)$$

  $$\Delta q(x,Q), \Delta G(x,Q)$$



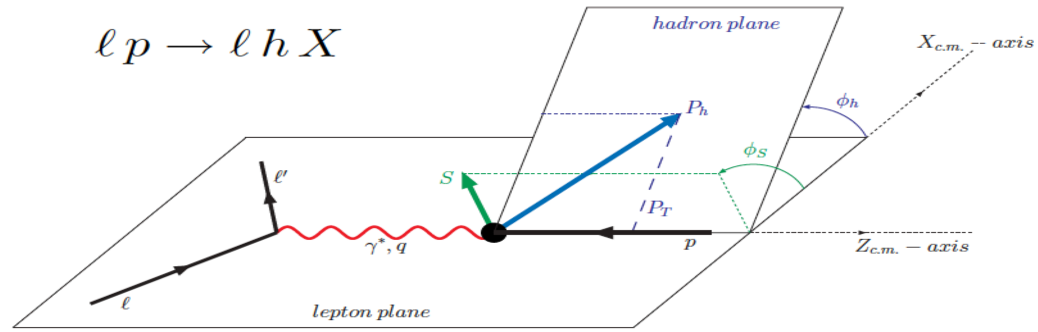
Nulceus A

- **Semi-Inclusive (2 scales):**

  3-D momentum confined motion

  $$q(x,k_T,Q), g(x,k_T,Q), \ldots$$

  Hadronization/fluctuation



- **Exclusive (1 hard + 1 soft scale):**

  1+2D imaging - GPDs

  $$H(x,\xi,t,Q), E(x,\xi,t,Q)$$

  $$\tilde{H}(x,\xi,t,Q), \tilde{E}(x,\xi,t,Q)$$

  Quark/gluon total angular momentum
  to proton's spin